TECHNISCHE UNIVERSITÄT DRESDEN

cfaed CENTER FOR ADVANCING ELECTRONICS DRESDEN

CENTER FOR ADVANCING ELECTRONICS DRESDEN

INTERIM REPORT 2012 - 2016

Contents

A Success Story...to be continued

Our Cluster has developed tremendously since its start of the funding period in 2012. I am proud that cfaed has already gained an international reputation as the place to go for advanced microelectronics research on beyond CMOS solutions. Our unique approach of integrating discovery-driven natural sciences and innovation-driven engineering, the international superstars we have recruited and the groundbreaking research results have helped to make cfaed visible and to promote it to a feisty player in the global scientific competition.

The enthusiasm of Cluster members during the past three years has truly impressed not only me but also those who were initially quite skeptical about our integrative, interdisciplinary approach and have now become convinced that cfaed's evergreen comprehensive 'More-shots-on-goal'-approach is indeed successful. Researching new and emerging materials, however jointly being investigated by circuit designers and system engineers, is a unique way of looking at the full development chain, from materials to systems.

Our investigators are publishing influential work in the subjects' most important journals: scientific breakthroughs include the first flexible light weight diagnostic platform and the world´s first universal transistor, fusing n- and p- type behavior with equal performance into a single device or the organic inversion field effect transistor. These achievements are being recognized by several prizes, important grants such as an ERC Advanced Grant, and international recognitions such as 'Highly-cited Researcher 2015'.

We have hired four strategic professors who will boost our work with new ideas and lead to dynamic ways of thinking and approaching new tasks. Their groups are growing exceptionally fast which is an excellent sign of the scientific popularity of the cfaed professors and vibrant network surrounding them.

Our distinct Career Development Program has supported young scientists and helped them to find their way, starting with the PhD degree, on to excelling their scientific careers until they will arrive in the desired position. We can already refer to several personal success stories based on our support measures.

The past three years were certainly two of the most memorable ones in my professional life: scientifically and personally challenging yet academically rewarding and satisfying. I invite you to glance through our midterm report and read about scientific results and personal achievements and to gain an overview of our work. We are always open to criticism, advice and constructive discussion and welcome your comments and any questions.

Sincerely Yours,

Prof. Gerhard Fettweis
Coordinator of the Cluster of Excellence cfaed

Pioneering Research

The Excellence Initiative of the German Federal and State governments has opened a chance for universities to excel in the international competition. TU Dresden has taken on this challenge and used it as an opportunity to become one of Germany's elite universities.

During the past years of systematic funding for distinguished research topics, highly efficient research structures have emerged. The Cluster of Excellence cfaed has grown into one of the global players in the area of microelectronics research and strengthens not only TU Dresden but also Dresden as Europe's largest hub for microelectronics. cfaed has attracted international top researchers and achieved influential results. Dresden has gained an international reputation for excellent research, state-of-the-art foundries and, most importantly, the close-knit network of industry and research institutions working together: fundamental and applied research on information processing and communication at TU Dresden, Leibniz, Fraunhofer, and Max Planck Institutes – this innovative DRESDEN-concept is a platform which provides excellent facilities leading to ingenious results. It creates a unique science spirit in Dresden that disperses into the global science community.

cfaed thrives on this spirit and first results pique curiosity: so in order to follow emerging new developments, the support of developing sustainable structures must be paramount for the Free State of Saxony. I therefore fully support cfaed's aim to become an international visible platform for advancing ideas in the field of microelectronics research and promise my commitment for this endeavor.

Best Wishes,

Dr. Eva-Maria Stange
Saxon State Minister for Higher Education, Research and the Arts

Onwards & Upwards!

As the Rector of the only University of Excellence in the states of the former East Germany, I am particularly proud about the very high quality and motivation of our researchers and young scientists, who shape the image of our university. These bright minds are spreading the word about the strength of TU Dresden and the unique possibilities in the Science State of Saxony. And even though the Cluster of Excellence cfaed is still a very young platform, it nevertheless has developed over the past three years into an internationally recognized center for microelectronics research. And with that, cfaed has grown into a flagship of our University.

I am deeply impressed by the commitment and dedication of the staff of cfaed with respect to their research work and their Cluster. The support of TU Dresden in terms of resources and structures is becoming increasingly visible, not at least through the progressing work on the new cfaed building which is financed by the Free State of Saxony. Once completed, it will unite natural scientists and engineers with a wide range of expertise and will become a truly concrete example for the synergies that are raised by the renowned cooperation between the University and the local world-class government research laboratories, the so-called DRESDEN-concept.

TU Dresden and the whole region will benefit from the forthcoming successes of cfaed, which will help to establish the University as a leading research center and strengthen the competitive industrial edge of Silicon Saxony, in the areas of microelectronics and semiconductors.

With this,
I wish cfaed all the best for the coming years!

Prof. Hans Müller-Steinhagen
Rector Technische Universität Dresden

A/ BOUT CFAED

“Semiconductors are the crude oil of the information age.”
John Fellows Akers,
former IBM chairman

cfaed at a Glance
Center for Advancing Electronics Dresden

Today, information processing is dominated by CMOS technology. As this conventional method is reaching atomic boundaries, new ways must be found to address the ever increasing and changing challenges of electronic information processing systems. It is the vision of cfaed that future CMOS technology will be complemented with new technologies (augmented CMOS), resulting in heterogeneous architectures to form highly efficient information processing environments.
The Cluster is set within Dresden's research network, underpinned by the alliance DRESDEN-concept, which stands for the vivid partnership of educational, research, and cultural institutions. cfaed is a unique chance to strengthen Saxony's position as largest microelectronics hub in Europe by establishing a strategically important world-class platform for fundamental research.

Unique Approach

- Integrating discovery-driven natural sciences and innovation-driven engineering
- Research Areas: Biology, Chemistry, Physics, Maths, Computer Science, Electrical Engineering
- 3 abstraction layers: Materials & Functions, Devices & Circuits, and Information Processing

Organization

- About 70 Investigators
- Approx. 300 scientists
- About 50% internationals from 30 nations
- 9 Research Paths
- 10 Partner Institutions

Infrastructure

- New building: under construction (projected completion 2017); €35 million financial volume
- Technology platform: Dresden Center for Nanoanalysis (DCN)
- Unique setting: DRESDEN-concept

Funding

- Cluster of Excellence at Technische Universität Dresden
- Funded by the German Research Foundation (DFG) 2012-2017
- Funding volume: €34 million

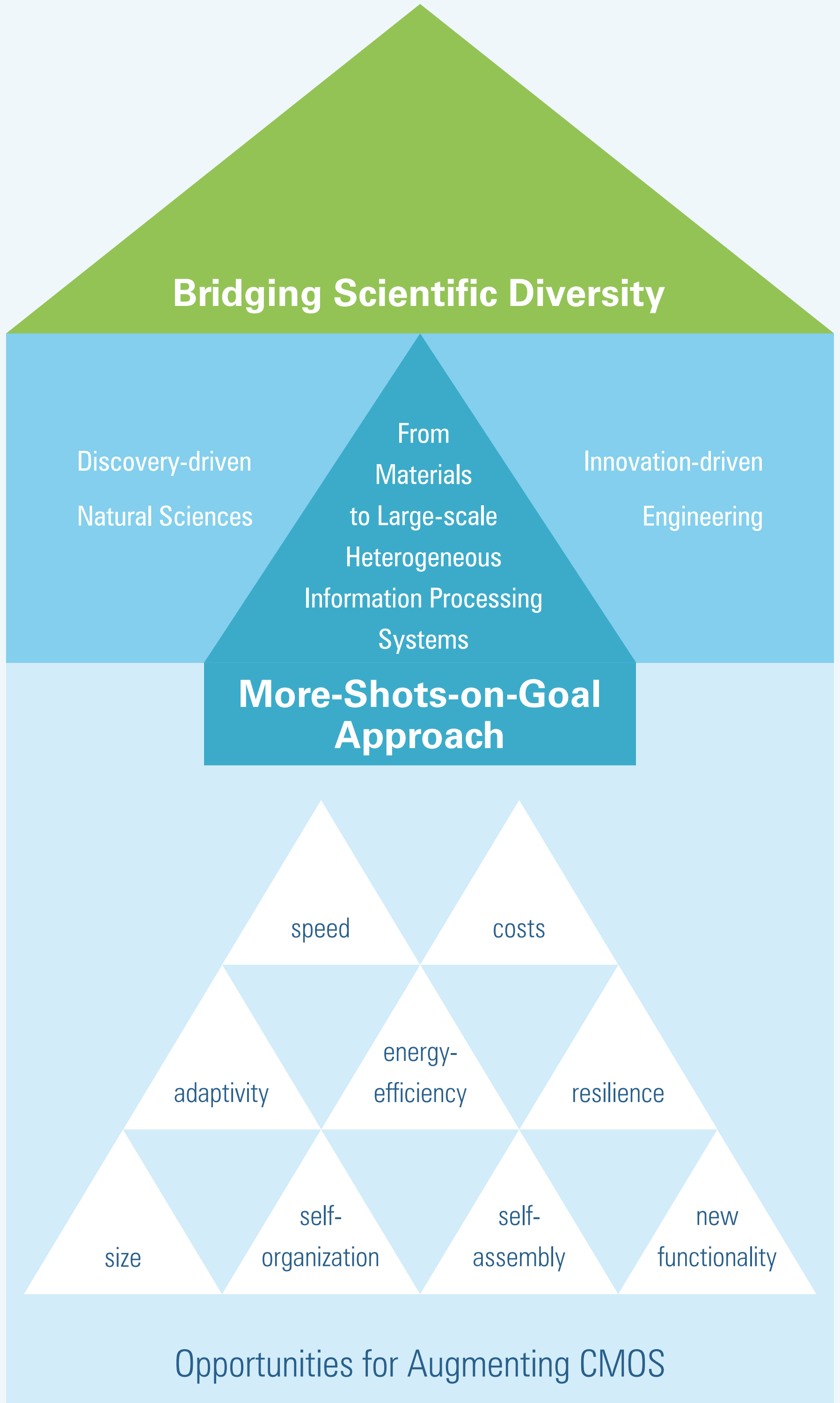
People

- 4 Strategic Professors & 9 Research Group Leaders
- About 80 PhDs & 40 Postdocs
- Career Development Program

Scientific Excellence

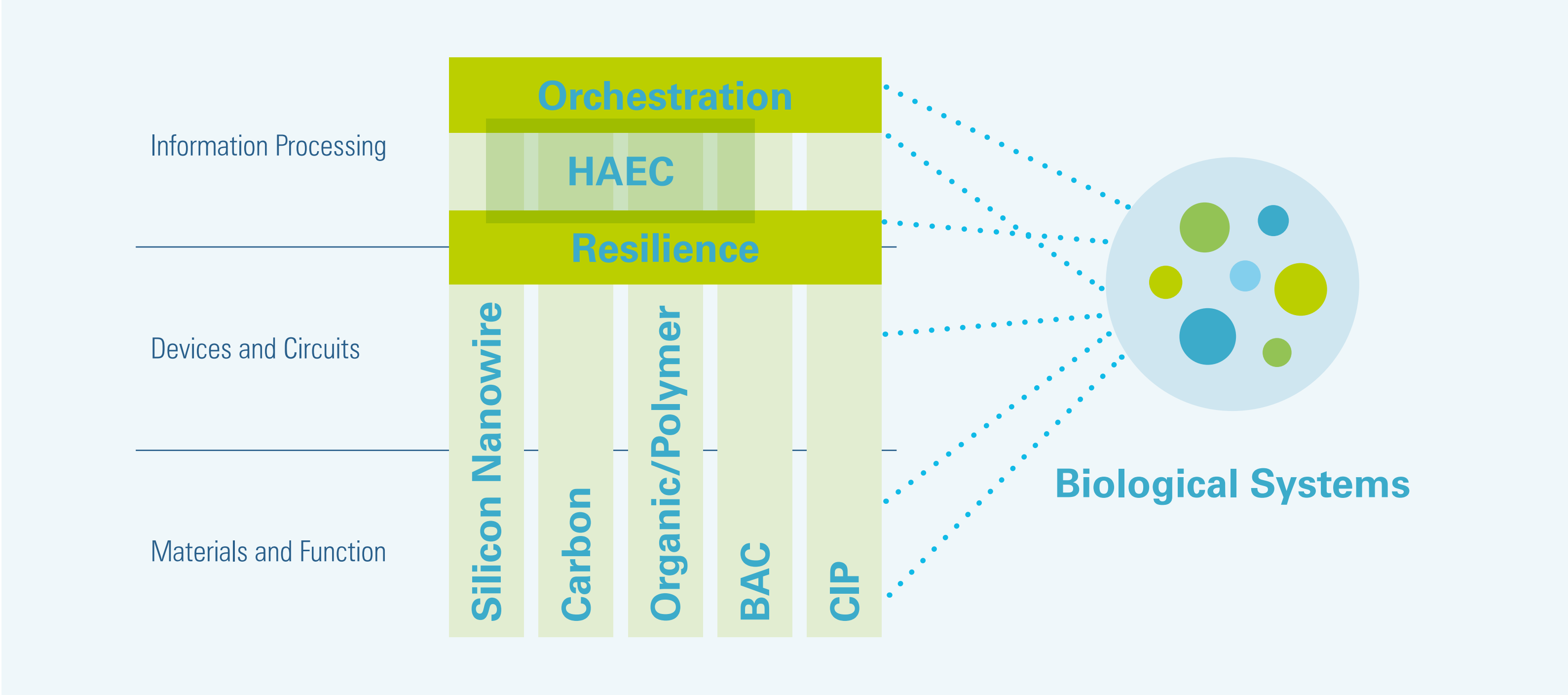
- Approx. 700 publications
- 2 ERC Advanced Grants / 2 ERC Starting Grants / 1 ERC Proof-of-Concept Grant
- 2 Highly Cited Researchers (2015)

Our Approach: Maximizing Chances for High-Impact Breakthroughs



Research Program: Path Structure

The myriad of applications for electronic systems have rendered the underlying semiconductor technology the most important driving force for innovation. As the advancement of this technology has started to approach boundaries, the Cluster of Excellence Center for Advancing Electronics Dresden (cfaed) targets breakthroughs in promising technologies to complement today's predominant technology (CMOS) and to address the major challenges in electronic information processing: small physical size, speed, energy efficiency, new functionality, self-assembly/-organization, adaptivity, resilience, and cost. To achieve its goals, the Cluster actively integrates discovery-driven natural sciences and innovation-driven engineering. In a comprehensive approach, the research spans from materials to heterogeneous information processing systems and vice versa. To maximize success and enable fruitful cross-fertilization, the Cluster follows a 'more-shots-on-goal' approach by pursuing multiple, interconnected Research Paths reflecting the distinguished research competence of Technische Universität Dresden (TUD) and its partners in cfaed.



Materials-Inspired Paths

Silicon Nanowire Path

Path Leader: Prof. Dr.-Ing. Thomas Mikolajick
Path Co-Leader: Prof. Dr. Gianaurelio Cuniberti

Silicon is being investigated for its very beneficial electronic properties and because silicon nanowires can be configured to change transistors between p- and n-type dynamically. The design of novel and fault tolerant computing algorithms that make use of the transistors' multi-functionality is investigated and silicon nanowires are explored as a selective sensor platform for biomolecules. In 2015, a flexible light weight diagnostic platform was realized that enables cost efficient high-volume delivery to medical institutions worldwide.

Carbon Path

Path Leader: Prof. Dr.-Ing. habil. Michael Schröter
Path Co-Leader: Prof. Dr. habil. Gotthard Seifert

Carbon nanotubes (CNTs) are being investigated for use in electronics for high frequency communication systems. Main emphasis is put onto the profound theoretical understanding as well as wafer-scale fabrication of the CNT-based electronics. Very recently, first transistors operating in the GHz regime were demonstrated.

Organic/Polymer Path

Path Leader: Prof. Dr. Stefan Mannsfeld
Path Co-Leader: Dr. habil. Francesca Moresco

The goal of the Organic and Polymer Path is to overcome some of the major limitations of organic materials and devices and thereby identifying the route towards new organic information processing systems. Research highlights include the controlled transport of single atoms by an electronically driven molecular nanostructure, a new concept for organic transistors with doped layers, and vertical organic permeable base transistors.

Biomolecular-Assembled Circuits Path (BAC)

Path Leader: Prof. Dr. Stefan Diez
Path Co-Leader: Prof. Dr. Dr.-Ing. habil. Michael Mertig

Nanostructures made from DNA allow to arrange functional materials in a scalable way to create self-assembled electronic, optoelectronic and nanophotonic devices that complement established silicon-based technologies. Recent achievements include the nanometer-precise placement of metallic nanoparticles for photonic waveguides and antennas as well as the controlled growth of metallic nanowires in DNA molds.

Chemical Information Processing Path (CIP)

Path Leader: Prof. Dr.-Ing. Andreas Richter
Path Co-Leader: Prof. Dr. habil. Brigitte Voit

The unconventional approach of the CIP-Path lays the foundation of transistor-based microfluidics for processing chemicals as information carriers. To reach this goal in the near future, two basic types of chemofluidic transistors have been developed. Current research focuses on a library of basic circuit technology. So far, chemofluidic oscillators and logic gates are demonstrated.

System-Oriented Paths

Orchestration Path

Path Leader: Prof. Dr.-Ing. Jerónimo Castrillón
Path Co-Leader: Prof. Dr.-Ing. habil. Jochen Fröhlich

This Path prepares the rapid and efficient implementation of heterogeneous systems by addressing adaptation inflexibilities of current hard- and software designs. The aim is the automatic adaption of applications and the underlying systems software to new heterogeneous CMOS and augmented CMOS systems. Recent achievements have been made on all layers of the stack reaching from the hardware layer up to the application layer.

Resilience Path

Path Leader: Prof. Dr.-Ing. Thorsten Strufe
Path Co-Leader: Prof. Dr.-Ing. Frank H. P. Fitzek

The goal of this Path is to achieve the resilience of networked systems, focusing on flexible, application-specific, and adaptive resilience mechanisms. Reliable information processing with unreliable and adjustable components is being researched, taking into account the projected heterogeneity of future systems and the fault characteristics of new materials-inspired technologies. The main achievements are reflected in a high number of publications at top-tier conferences and best paper awards.

DFG CRC 912

HAEC – Highly Adaptive Energy-Efficient Computing

Speaker: Prof. Dr.-Ing. Dr. h.c. Gerhard Fettweis

HAEC aims at enabling integrated hardware/software system solutions for distributed networked applications to be optimized for high adaptivity and energy efficiency during design as well as deployment, without compromising in performance. During Phase I (years 1–4), single technology demonstrators have been developed to illustrate and verify the achieved research results. A second funding phase was granted until 2019.

Discovery Path

Biological Systems Path

Path Leader: Prof. Dr. Marino Zerial
Path Co-Leader: Prof. Dr. Ivo F. Sbalzarini

This Path studies emergent behavior and information processing in biological systems and identifies principles that underlie biological function and could be beneficial for engineering applications. Initial understanding has been gained: How cells synchronize their chemical clocks over communication lines with a time delay that exceeds the oscillation period of the clock. How nature addresses complex high-dimensional optimization problems. How cells take decisions in the face of noise and uncertainty.

“Nanotechnology will let us build computers that are incredibly powerful. We'll have more power in the volume of a sugar cube than exists in the entire world today.”
Ralph Merkle

Nanowire Sensors: Light Weight and Flexible High-Performance Diagnostic Platform

Integrating silicon nanowires (SiNW) into electronic networks to assure the high performance and exceptional sensitivity of the resulting devices, suitable for sensorics applications, was the main challenge for the scientists involved in this project. It comprises the whole process chain from synthesizing the sensors up to testing in real environment and characterizing. The group envisions broad applications of such devices for future bio-medical diagnostics, using isolated DNA strands, bacteria or specific markers for diseases. Remarkably, such systems can be successfully implemented for both conceptual realizations of the diagnostic platforms, for (a) complex clinical analytics – using multiplexing and (b) point of care detection (POC), relying on the use of cost efficient, light weight and shapeable materials. "In spirit of the POC approach, a new achievement we recently accomplished was applying such a SiNW sensor on a flexible platform. We have proven a way to attach such sensors on a bendable, flexible substrate which directly could be applied, e.g., on a patient's skin. A flexible diagnostic platform was realized and demonstrated for early detection of avian influenza virus (AIV) subtype H1N1 DNA sequences with the sensitivities down to picomolar range," summarizes Dr. Larysa Baraban.

Method

The working principles of ion sensitive field effect transistors based on silicon nanowires are well-known. The appearance of a molecule at the surface of SiNW acts like a 'biological gate', since the surface potential in the nanowires changes. "Thus, a molecule substitutes the electronic gate known from the classical transistor," describes the group. The sensing works via functionalized layers using the chemical properties of molecules to bind on certain substances and not to bind to others. By applying these binding anchor molecules, the scientists can functionalize these layers. This makes them extremely selective and adaptive. The solution or the liquid is streaming directly over the nanowire surface. In addition, the nanowire sensors can be used also in air or in other gases.

Why are SiNW 'hot' for sensing?

Due to their special structure with a long but very thin shape, nanowires comprise a really high surface/volume ratio. On a given volume, they have a very big surface making them highly sensitive. So the scientists can set up an array of a few nanowires that are functionalized in a selective way to detect different markers – the result is a multiplexed sensor. This enables the researchers to detect for example many different molecules on a compact scale. Use of such kinds of sensors helps to reduce the volumes of the liquids, necessary for analysis. Recently, the scientists realized a flexible light weight diagnostic platform enabling a cost efficient high-volume delivery to medical institutions worldwide – and gained a cover story at issue 10/2015 of 'Advanced Healthcare Materials' journal.

Detecting the avian influenza virus

The platform is based on highly sensitive Si nanowire field effect transistors (SiNW FETs) fabricated on flexible polymeric foils, which are only 100 µm thick. The devices reveal a remarkable limit of detection for subtype H1N1 avian influenza virus, which is considered as a global major risk for human health, exemplified by the declaration as pandemic to the 2009 swine-origin one. The devices on polymeric support are about 10 times lighter compared to their rigid counterparts realized on conventional Si wafers which make them cost-efficient for high-volume delivery to medical institutions worldwide. The researchers envision that this sensitive and cheap diagnostic platform will enable also the developing countries to detect and counteract viral or infectious diseases.

Outlook

The main advantage of this new technology is enabling much smaller medical devices, what widens areas of their potential applications, spanning from the POC medical diagnostics up to wearable electronic gadgets for life quality monitoring. The SiNW sensors have to be cheap and easy to handle. The data could be collected by smartphone and is sent to an expert who does the analyzing. To take out one example: in human sweat there are biomarkers which can be detected by a sensor attached to the skin. The technology is ready but there is still a long way to go with testing, calibrating, and optimizing. "There is a lot of work to do when heading for the 'multiplexing' – to avoid that one molecule works as the other. And we have to find solutions to receive the harvested data as lean as possible – there is a lot of noise coming out and we think about cleaning the data already on the spot where it is produced", the group sums up the future perspectives.

Networked research

Baraban points out the special acceleration that the Cluster provides: "cfaed has a special effect on our work. There are scientific cooperations inside and outside the SiNW Path. There is already a lot of knowledge of integrating SiNW in electronics, in circuits – this is very crucial for us to rely on these resources. Our research topics are also connected to the work of the Carbon Path, and we have linking elements to the Organic Path. Also, we found great expertise in the CIP Path, the scientists there have a lot experience in dealing with very small amounts of liquids. Cooperation emerged and joined projects are still being developed". A good example for these benefits is the above-mentioned achievement: The flexible sensing platform was produced out at the Leibniz Institute for Solid State and Materials Research Dresden (IFW) in cooperation with the Chair of Materials Science and Nanotechnology of TU Dresden and NaMLab gGmbH.

Collaborators:
Larysa Baraban, Gianaurelio Cuniberti, Bergoi Ibarlucea, Denys Makarov, Thomas Mikolajick, Sebastian Pregl, Oliver G. Schmidt, Walter M. Weber, et al.

Institutions:
cfaed; NaMLab gGmbH; TU Chemnitz; TU Dresden; IFW Dresden

Path: Silicon Nanowire

DOI: 10.1002/adhm.201570057

Phys EE

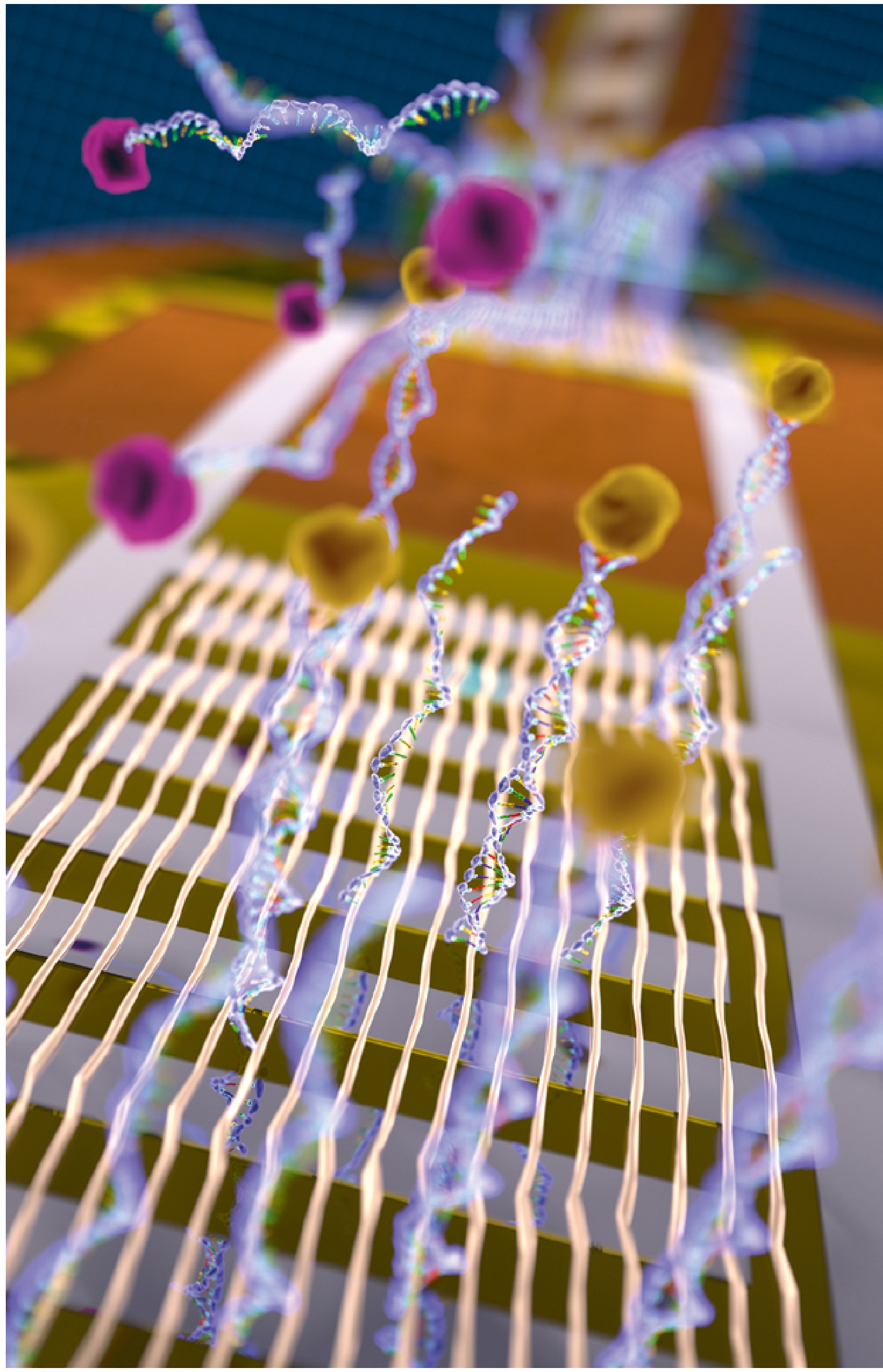


Illustration of a flexible DNA nanosensor based on silicon nanowires

World´s First Universal Transistors Fusing n- and p-Type Behavior with Equal Performance into a Single Device

Scientists at cfaed and the Nano-electronic Materials Laboratory (NaMLab gGmbH) have demonstrated the world's first universal transistor that truly delivers equal performance for n- and p-type response. Dr. André Heinzig demonstrated energy efficient CMOS circuits with one simple transistor type instead of the two different types which up-to-date have significantly differed in composition, technology, and size. The new technology could change the current major CMOS technology significantly enabling a single MOS technology (SMOS).

The challenge

The vast majority of today's digital circuits relies on complementary logic (CMOS), where p- and n-type transistors are alternately switched to reduce standby-power consumption. For over 40 years p- and n-type transistors have been designed, scaled and optimized individually in order to achieve equal and therefore compatible electrical performance. For compatibility in circuits the total on-currents, switching slope and magnitude of the threshold voltage have to be equal in p- and n-type transistor. This has been a difficult task, given the different nature of p- and n-type conduction in silicon.

SiNW transistors with equal p- and n-type performance

The universal transistor jointly developed by NaMLab and cfaed solves these disparities by merging the characteristics of p- and n-type transistors into a single device with selective electron and hole injection valves. The ratio between electron and hole injection is mainly tuned by strain incorporation. The work of André Heinzig and Walter M. Weber appeared in the Journal Nano Letters and describes, for the first time, fully functional silicon nanowire transistors with equal p- and n-type performance and CMOS circuits built thereof.
In addition, single MOS technology has enabled the first realization of truly complementary reconfigurable circuits, with a single supply voltage. The multiple operation states of these transistors open new opportunities for logic circuit design. A higher number of functions can be computed with the same hardware complexity as conventional CMOS electronics.

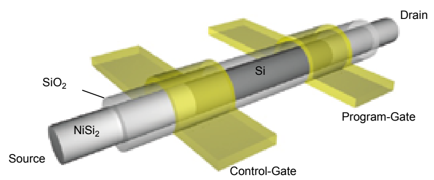
Simplifying the fabrication process

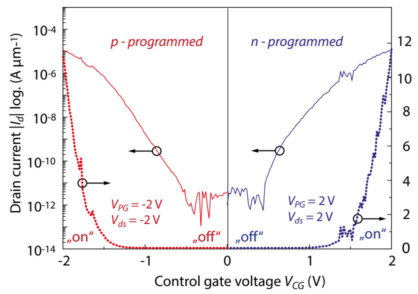
Two interesting circuit strategies that were previously not accessible with conventional FETs are currently being explored. In the first one, layout generation and mapping of circuits is reduced to a single type of universal device of a sole material composition and size. This is distinctly different to state-of-the-art CMOS, where designs cope with different compositions, size, shared implantation wells and local isolations between different wells. In the second strategy, new types of circuits can be studied, that can have multiple functionalities as programmed on-the-fly through the individual signals.

Due to the reconfigurability of our single MOS approach an increased value per building block is delivered. One basis is given by the compact six transistor NAND/NOR cell developed by Jens Trommer and André Heinzig. Distinctly, this cell always operates in a complementary manner, reaching a full swing output and exhibiting the same delay for both functions. The other basis is the integration of multiple gate electrodes along the nanowire channel, lumping various series transistors within a single one showing the same on-resistance as dual gated device and sparing interconnects and area for isolations and wells.

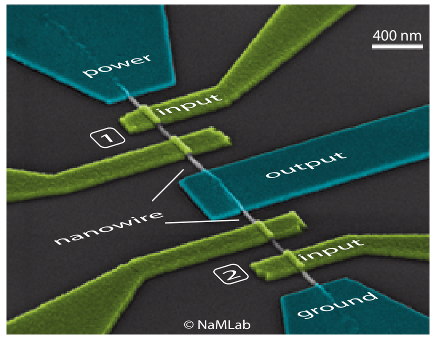
Functionality enhanced logic gates

In the Nanowire Group a comprehensive library of functionality enhanced logic gates has been shown. A prominent example is given by a 1-bit adder by Jens Trommer and Michael Raitza which only employs 16 transistors vs. typical CMOS implementations with 28 transistors. In addition, critical paths are significantly reduced leading to a reduction of the overall structural delay by approximately 50 %. Proper radial scaling and the implementation of germanium channels can boost performance in terms of significantly lower dynamic power consumption and lower the intrinsic delay.





Schematic of the universal transistor realized by independent Schottky gating on a strained silicon nanowire core and the measured unipolar transfer characteristics for p- and n-programmed mode showing symmetry over the full voltage range



The unique single MOS technology is a promising route to continue the virtuous economic cycle of electronics beyond conventional Moore's scaling as it extends the functional diversity of the basic electronic devices, the transistors.

Collaborators:
Daniel Grimm, André Heinzig, Thomas Mikolajick, Jens Trommer, Walter M. Weber, et al.

Institutions:
cfaed; IFW Dresden; NaMLab gGmbH; TU Chemnitz; TU Dresden

Path: Silicon Nanowire

DOI: 10.1021/nl401826u

Phys CompSc EE

Hybrid Nanomembrane Superlattices for Thermoelectric Applications

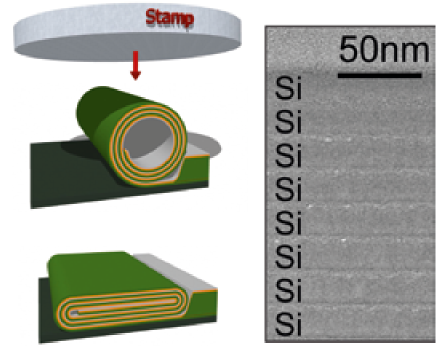
cfaed scientists of the Silicon Nanowire Path (SiNW) at Leibniz Institute for Solid State and Materials Research Dresden (IFW) and TU Chemnitz constructed a new type of hybrid nanomembrane superlattices for thermoelectric applications. Continuously increasing demand on energy supply of world population will become a critical problem for the current century as the fossil fuel supplies are decreasing. The need for alternative sources of energy, as well as the most efficient conversion of energy have triggered significant research on the material sciences and device integration. Thermoelectric materials, which are capable of converting heat directly into electricity as a thermoelectric generator or vice versa using the electrical power for refrigerating, have received much attention because of their high reliability and environmental friendliness. Yet, challenges remain on how to improve the electricity generation efficiency of thermoelectric devices.

Method

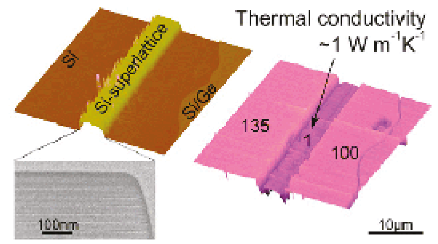
The superlattices can consist of an arbitrary composition of n- or p-type doped single-crystalline semiconductors and/or a polycrystalline metal layer. These hybrid multilayered systems are fabricated by taking advantage of the self-rolling technique. First, differentially strained nanomembranes are rolled into three-dimensional microtubes with multiple windings. By applying vertical pressure, the tubes are then compressed and converted into a planar hybrid superlattice (see upper figure). The scanning thermal atomic force microscopy measurements support the observation of reduced thermal transport on top of the superlattices (see lower figure). In addition, small defects with a spatial resolution of ~100 nm can be resolved in the thermal maps. The low thermal conductivity reveals the potential of this approach to fabricate miniaturized on-chip solutions for energy harvesters in, e.g., microautonomous systems.

Result

These hybrid superlattices consist of a large number of nanomembranes mechanically stacked on top of each other, which are fabricated by a roll-up and compression technique. Thermal transport measurements reveal a two orders reduction of the cross-sectional heat transport through this nanomembrane superlattice compared to that of a single nanomembrane layer. The rolling-up method is an elegant combination of conventional 2D deposition techniques and standard semiconductor processing technologies, which offer excellent device control and integration. The low thermal conductivity of the fabricated hybrid superlattices has the potential to support on-chip solutions for energy harvesters in e.g. micro-autonomous systems.
A substantial thermal transport reduction of two orders of magnitude is achieved in all the investigated nanomembrane superlattices. By combining the absolute values of two different methods, a better understanding of the thermal transport properties of the hybrid superlattices is achieved. These results offer a promising path to reduce the thermal conductivity by the incorporation of mechanical interfaces. By the roll-up and compression technique, a large variety of different types of interfaces with different materials such as metals, semiconductors, oxides, and molecules can be produced. The technique allows the straightforward integration of single-crystalline p- and n-type semiconductors necessary to fabricate thermoelectric generators.
The thermal measurements show a substantial reduction of the cross-sectional heat transport through the nanomembrane superlattice compared to a single nanomembrane layer. Time-domain thermoreflectance measurements yield thermal conductivity values below 2 W m^{-1} K^{-1}. Compared to bulk values, this represents a reduction of two orders of magnitude by the incorporation of the mechanically joined interfaces.



Compression of a rolled-up nanomembrane into a novel superlattice type



Topography (left) and thermal conductivitiy (right) of compressed superlattice

Collaborators:
Guodong Li, Mark H. Rümmeli, Oliver G. Schmidt, et al.

Institutions:
cfaed; TU Chemnitz; IFW Dresden; MPI Intelligente Systeme; University of Illinois

Path: Silicon Nanowire

DOI: 10.1021/nl404827j

Bio Phys EE

From Transistor Physics to Real World Applications
– a Multi-Scale Approach

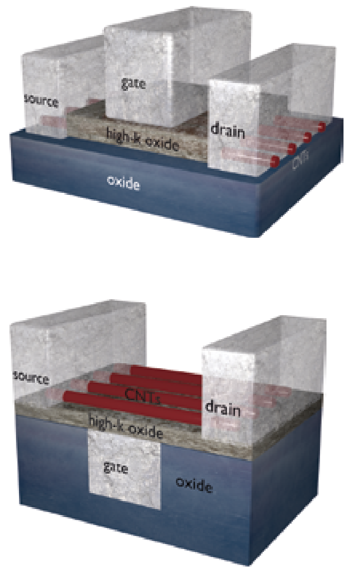
The development of a new transistor technology and the exploration of a new transistor functionality demand a high investment of time and money in the lab finding proper materials and technology recipes allowing the manufacturing of the transistors. Ideally, the fabricated transistors offer the expected functionality and allow the exploitation of the new transistor properties in circuits and applications. In the Carbon Path, a Carbon nanotube transistor (CNTFET) technology has been developed which should exploit its intrinsic potential for high speed and low-distortion signal processing. In contrast to other attempts worldwide, the technology development in the Carbon Path has been guided and supported by strong research activities in the field of modeling and simulation. Both, modeling and simulation deepen the understanding about the relevant physics in CNTFETs and pave the way toward the exploration of low-distortion signal processing which is attributed to the unique intrinsic linearity in the transfer characteristic of Schottky barrier CNTFETs. The modeling-driven technology development helps to find suitable device architectures as well as proper materials for the metals and oxides involved in the manufacturing of the transistors. In addition, special transistor models are developed for enabling computer-aided circuit design. Both aspects, supporting and guiding the technology development as well as enabling circuit simulation, are the cornerstone of the modeling-based bridge between the manufacturing on one side and the applications on the other side (fig. 2).

Applied methods

The device physics can be described at different length scales, levels of complexity and physical basis. In the Carbon Path, CNTFETs are studied at the atomistic level, the device level and the terminal level (fig. 3). At the atomistic level, specific parts of the whole transistor are described by atoms and their atomic interactions. Typically, the simulation times can span days for a single simulation run. For this reason, the numbers of atoms need to be limited. To facilitate simulations of the whole device as fabricated and to enable device optimization, specific macroscopic models such as Boltzman transport equation or effective-mass Schrödinger equation are employed, which neglect the atomistic effects but capture the essential transport physics in transistors. However, the simulation times still span minutes to hours for a single device. Thus, for the simulation of circuits with hundreds or thousands of transistors, compact models are employed. These models consist of a set of easy to solve analytical equations and sets of parameters for adjusting the model to a specific technology. To allow early circuit design studies for exploring the potential performance gain by introducing a new technology, early-stage compact models are developed, which comprises empirical equations, which can capture experimental data only. For a detailed understanding of a technology and to be able to predict and optimize the circuit behavior before fabricating the transistors and circuits, a physics-based compact model is essential, which links technology parameters with the transistor performance.

Results and discussion

For the Carbon Path a multi-scale modeling and simulation framework has been developed, which provides simulation tools at each level AND physical justified links in between the different levels of abstraction. This makes the developed framework for CNTFETs unique worldwide. For the description of the interface between the contact metals and the CNTs, an atomistic-based simulation tool has been developed since this interface is the most critical part for understanding the transistor behavior. At the device level, the software toolbox COOS has been developed which enables the simulation and understanding of CNTFETs from a few nanometers up to even micrometer long channels. The contact models within COOS are calibrated and physically justified based on the simulation done at the atomistic level. For circuit simulations, the early-stage compact model CCAM for the simulation of high-frequency analog CNTFETs has been developed and has been made available worldwide at the online platform nanohub.org. Improvements of the physics-based compact model TCAM includes simulations for high voltages as needed for high frequency CNTFETs. Both compact models are based on the modeling and simulations performed with COOS. The developed multi-scale simulation and modeling framework has been employed to define transistor architectures with promising low-distortion signal processing due to high device linearity. Simulations at the device level have shown the buried-gate architecture to have superior device behavior compared to the traditional top-gate architecture. The critical point for the device optimization towards high device linearity is to find material combinations providing small near-contact barriers where the current needs to go through. The contact metal significantly affects these barriers and the developed atomistic simulation tool gives for the first time meaningful guidelines which metals should be chosen and the developed hetero-junction contact model maps these atomistic findings to the device level. While fabricating the CNTFETs, defects can accidently be introduced into the CNTs. Even a single defect can already change the transistor properties and can lead to a meaningful mismatch between fabricated transistors in terms of threshold voltage and maximum current depending on the location of the defect along the channel. The more defects, the higher are the statistical variations across the fabricated samples (fig. 4). The multi-scale simulation framework has been designed to predict these correlations. The investigation of the contacts and the impact of the defects on the transistor performance are two examples for the capability of the multi-scale simulation framework for increasing significantly the understanding and the chance to exploit the unique features of CNTFETs in real applications.



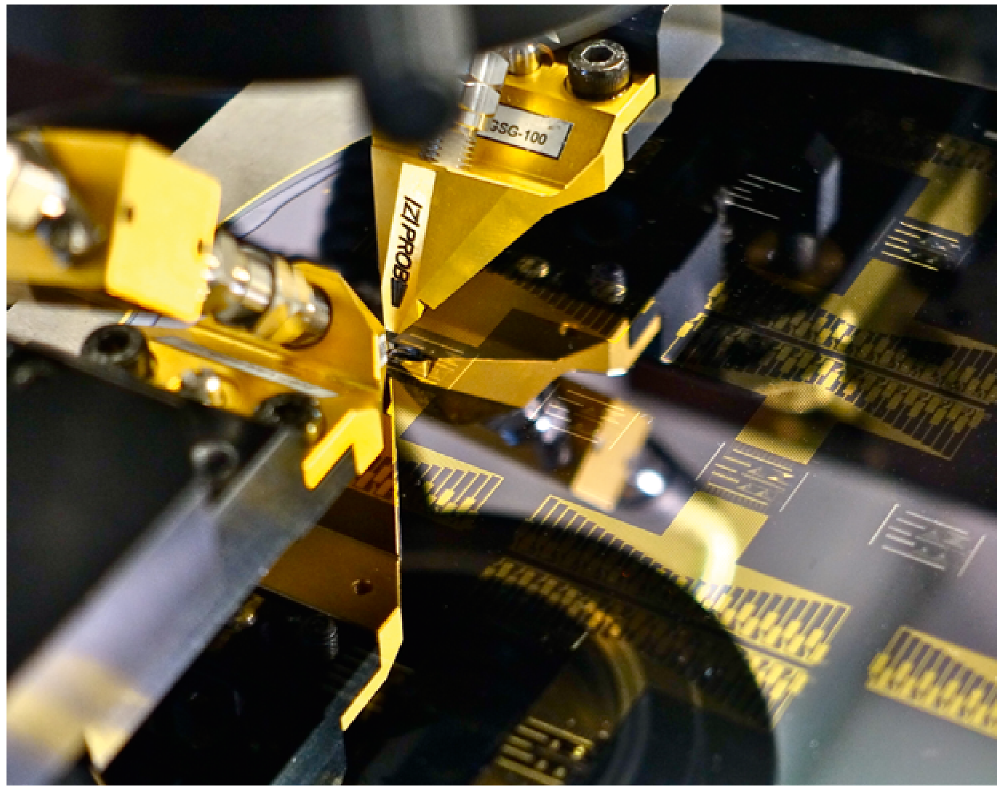


Fig. 1: Common CNTFET architectures: top-gate and buried-gate and fabricated buried-gate transistors on a wafer (contacted with probes for electrical device characterization)

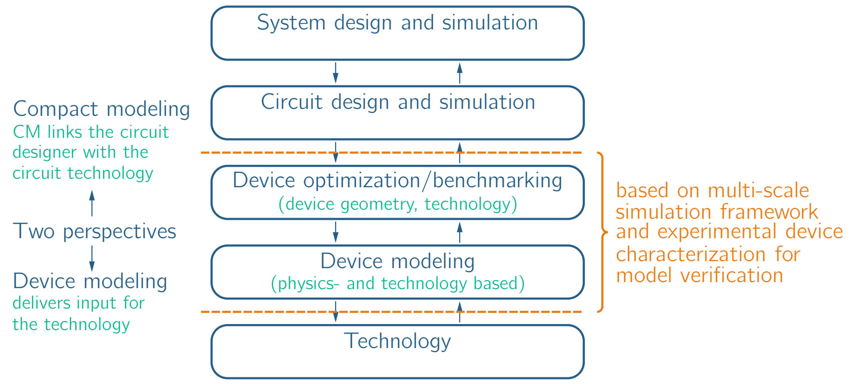


Fig. 2: Device modeling bridges the large gap in between circuit fabrication with circuit design.

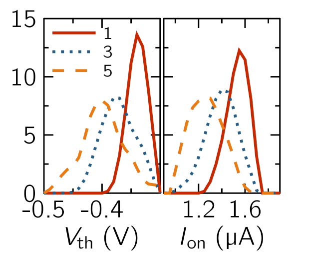


Fig 4: Impact of random defects on transistor parameters such as threshold voltage V_{th} and maximum current I_{on}. The different curves represents different numbers of fixed randomly distributed defects along the CNT.

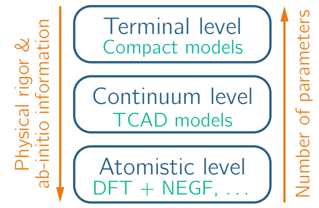


Fig 3: Different abstraction levels for describing transistor physics

Collaborators:
Martin Claus, Michael Schröter, Stefan Blawid, Zhenan Bao, Eric Pop, Joachim Knoch, et al.

Institutions:
cfaed; TU Dresden; Universidade de Brasília; Stanford University; RWTH Aachen

Path: Carbon

DOIs:
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10.1109/TNANO.2015.2397696

Chem Phys CompSc EE

Technology Development for Analog High Frequency Carbon Nanotube Transistors

The scientists around Dr. Sascha Hermann combine the extensive and complementary multi-disciplinary CNT-FET competences in Dresden and Chemnitz covering materials science, multi-scale device modeling, RF circuit design and fabrication, and wireless communications. The Carbon Nano Devices (CND) group at the Center for Microtechnologies and Fraunhofer ENAS in Chemnitz is mainly dealing with the technology development and device fabrication. They follow a disruptive technological approach by bringing all nanomaterial integration process steps to the wafer-level.

Method

Building up a CNT-based transistor with scalable technologies covers fabrication of multi-layered peripheral FET structures, adjusting of CNT-material properties, assembly of CNTs, contact engineering, and tuning of the FET channel properties. A technology platform has been established to enable the fabrication of FETs in a special HF adapted layout, as well as large arrays of FETs for in-depth statistic electrical studies on different aspects along the fabrication chain. Advanced analytical methods such as in-situ process monitoring were used and developed. Research on novel nanofabrication steps such as in-situ channel polymerization and even new architectures such as all-Carbon FETs are under investigation.

HF-FETs

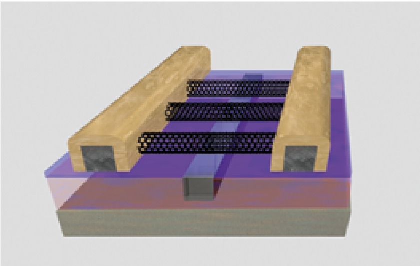
CNT-FETs were fabricated in a special high frequency layout on 150 mm wafers. To minimize parasitic capacitances, a local embedded bottom gate electrode has been realized via damascene technology. In order to enable a low impedance level and high currents in HF operation, FETs in multi-tube configuration were fabricated. CNT assembly was performed by dielectrophoresis, which has been further developed to a wafer-level process in Hermann's group. Semiconducting enriched single-walled CNTs reaching purity levels as high as 99,9 % were used as CNT material. Since CNT/metal contacts are important for the device performance, contact engineering is one of the aspects under development and investigation. The researchers have fabricated two transistor generations with improved performance. Extended electrical characterization on the first HF-FET generations, which used 50 nm SiO_2 gate dielectric and 0.8 µm channel length, operated already at a transit frequency of up to 3 GHz. Ongoing work in the 3rd and 4th generation focuses on higher device performance by shrinkage of device dimensions, integration of high-k gate dielectrics and technology optimization.

Transistor channel engineering

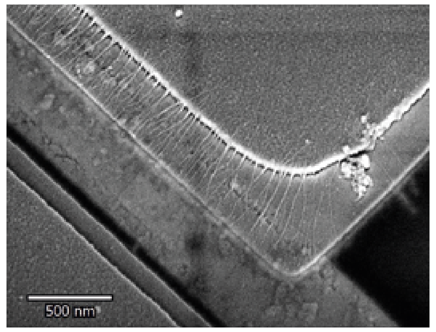
Since dielectrophoresis is a liquid-based technique where surfactant molecules are involved to maintain a stable CNT dispersion, it is important to examine procedures for removal of chemical residuals which may be considered as potential charge trap affecting the FET performance. Four different approaches for cleaning the integrated CNTs were investigated by means of statistical studies on more than 600 CNT FETs. Through combining XPS, Raman spectroscopy, and electrical studies it turned out that especially DI-H_2O and HNO_3 treatments appeared to be most effective for the removal of surfactant residuals. The on-current was strongly enhanced by the HNO_3 cleaning procedure. Equally, there was a pronounced influence of a subsequent annealing treatment apparent, which drastically affects the hysteresis behavior and reduces the device-to-device variance.

In-situ polymerization

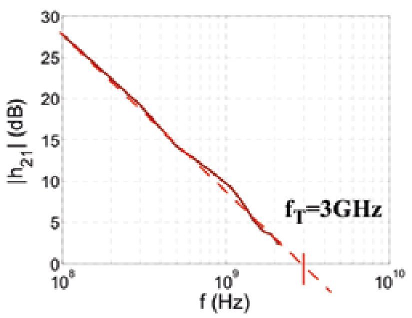
Another aspect under investigation is related to the prevention of agglomeration in dense CNT assemblies along or after liquid processing. CNT bundles lower the maximal current, reduce the transistor operation frequency, and deteriorate the whole switching behavior. To tackle this issue, the group integrated a unique technological approach based on in-situ polymerization directly from the surface of the CNTs arranged in the FET channel. Together with Prof. Jordan's group at TUD, Hermann's group could show a significant improvement of the FET characteristics in terms of on/off ratio, mobility and even conductivity. Sodium styrenesulfonate was polymerized by a self-initiated photografting and photopolymerization process directly from the surface of the CNTs leading to a splitting up of CNT bundles. Subsequent vacuum annealing was found to induce ambipolar behavior, which could be conserved upon long term storage under ambient conditions.



Schematic of multi-tube field-effect transistor in local bottom gate configuration



Electron microscopy image of a FET site showing different structuring levels as well as densely aligned single-walled CNTs



High-frequency electrical characterization of 2nd generation HF-FETs showing the current gain over frequency for VDS = 4V

Collaborators:
Sascha Hermann, Thomas Geßner †, Martin Hartmann, Rainer Jordan, Jana Tittmann-Otto, Stefan E. Schulz, Marius Toader

Institutions:
cfaed; Fraunhofer ENAS, TU Chemnitz; TU Dresden

Path: Carbon

Chem Phys EE

CNT Sorting: Semiconducting Enrichment of sc-SWCNTs

Sorted single-walled carbon nanotubes (SWCNTs) are necessary for source-drain channels in field-effect transistors (FETs). By using density gradient ultracentrifugation (DGU), Linda Scharfenberg produces homogeneously sorted CNTs that are needed by technologists.

Method

Due to their intrinsic properties, SWCNTs are promising candidates for source-drain channels in CNT-FETs. To efficiently build those CNT-FETs, technologists need CNTs that are homogeneously sorted according to properties such as electrical type (metallic or semiconducting), chirality, length, or diameter. The application of CNTs in transistors requires semiconducting tubes, and thus, sorting of SWCNTs according to those needs. Scharfenberg had to find the proper solution to fulfill the special demands. As CNTs are hydrophobic and normally clustered they first have to be separated. This is normally done by adding surfactants and applying ultrasound. However, the application of ultrasound might cause the CNTs to break which is a negative side-effect as it is desirable to have long CNTs (on average 1.5 µm).

The basis for an efficient sorting is the dispersion of the material. Methods to achieve it usually include – but are not limited to – applying tip sonication in the presence of appropriate amphiphilic molecules. Scharfenberg presents a high semiconducting enrichment of surfactant-wrapped arc discharge SWCNTs. The sorting according to electronic type is realized by applying DGU. She utilized a common combination of anionic surfactants, but optimized the sonication time during the dispersion step and the duration of performing DGU. Furthermore, Scharfenberg used UV–Vis spectroscopy to determine the differences in the content of metallic (m) and semiconducting (sc) SWCNTs of different samples.

Result

The result of the centrifugation process is that CNTs with certain characteristics float until the buoyant density is reached. After that, the gradient station will strip down layer by layer and sorted CNTs will emerge. Scharfenberg has published a paper describing this process with the result of 98 % of homogeneous semiconducting CNTs after a two-step sorting process. This method is very time consuming but cfaed members at TU Chemnitz, namely the group of cfaed RGL Sascha Hermann, rely on Scharfenberg's delivery of nicely sorted CNTs. Currently, she works on sorting CNT by their chirality applying DGU.

Challenging first steps

After completing her Master at TU Dresden and writing the thesis at the Leibniz IPF, Scharfenberg applied for a PhD position at cfaed and was hired by Professor Michael Mertig (Chair of Physical Chemistry, Measurement and Sensor Technology). Sorting CNTs according to their electronic properties by DGU was a fairly new method as it had first been used only 2006. At first, Scharfenberg faced several challenges, including the acquisition of the necessary equipment: the ultracentrifuge and the gradient station. As the first person to actually sort the CNTs by defined characteristics, Scharfenberg experienced considerable difficulties to find any scientific material on that topic. She came across a highly cited paper by Michael S. Arnold (USA) "Sorting carbon nanotubes by electronic structure using density differentiation" (2006) and first tried to achieve the same results as this group by imitating the process that was described.

Collaborators:
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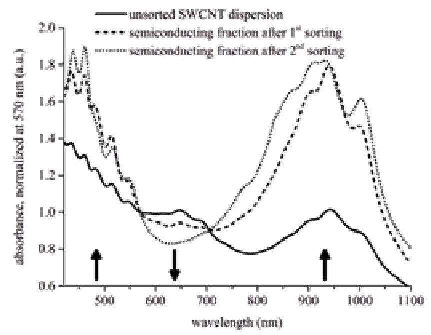
Institutions:
cfaed; TU Dresden; TU Chemnitz; Fraunhofer ENAS; KSI Meinsberg

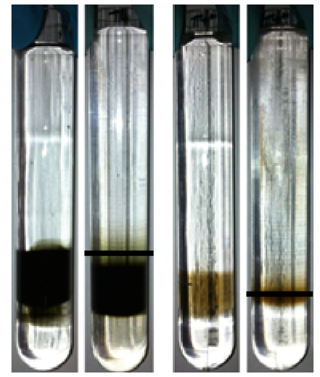
Path: Carbon

DOI: 10.1002/pssa.201431771

Chem Phys EE



UV-Vis spectra of the unsorted SWCNT dispersion, the highest semiconducting fraction after first sorting and second sorting. For a better comparison, the curves were normalized at 570 nm.



Photographs of the centrifuge tubes before and after DGU. The black lines in the photographs indicate the positions of the highest semiconducting fractions after each sorting.

Organic Inversion Field Effect Transistor

Controlled doping of semiconductors leads to highly reproducible transistors with precisely tunable device characteristics, which is witnessed by the success of inorganic metal-oxide-semiconductor field-effect transistors. However, most surprisingly, organic field-effect transistors (OFETs) almost exclusively use electrically undoped semiconductors and OFETs with doped channels are rarely reported. In 2013, scientists of the Institut für Angewandte Photophysik (IAPP) at TU Dresden realized an inversion transistor based on organic semiconductors. The inversion field effect transistor is the basic device of modern silicon based microelectronics and is nowadays produced more than a billion times in mobile phones and computers. Doping of organic semiconductors, which is already used successfully in organic light emitting diodes for displays of mobile phones and in organic solar cells, was the key to this invention. The breakthrough was published in 'Nature Communications'.

Method

Previously, doping had only rarely been used in organic transistors. "It has been assumed that doping either causes a deterioration of the transistor parameters, or that it is even not possible to realize organic inversion transistors." explains Dr. Björn Lüssem, the former head of the New Devices group of IAPP. However, organic doping can indeed be used in organic transistors. "The operating parameters can be precisely tuned in doped transistors," summarizes Lüssem.

Doping has previously only been used in depletion type OFETs. In these devices, doping on the one hand results in a detrimentally low ON/OFF ratio for higher dopant concentrations, on the other hand the beneficial effects on the transistor behavior, for example, on the threshold voltage, were limited at lower concentrations.

In contrast to depletion type transistors, where doping is used to enhance the already n-type or p-type nature of the channel region, in organic inversion transistors a positively charged p-type inversion layer is created in an n-doped channel layer, or vice versa. This type of devices has not been realized with organic semiconductors so far. The main challenge of reaching the inversion regime is the accumulation of minority charge carriers at the interface to the gate insulator.

Organic circuits are flexible and can be processed on large areas, making them an attractive technology for the design of novel electronic products. Nowadays, they are already used to control larger displays. Furthermore, medical applications as well as flexible displays and sensors are envisioned.

Result

"The first realization of an organic inversion transistor is a breakthrough for the field of organic electronics," confirms Prof. Karl Leo, director of the IAPP. "It shows the innovative strength of TU Dresden in information technologies and demonstrates that cfaed facilitates new cutting edge research. This success could only be achieved by close collaboration between our researchers and local industry, in particular by cooperation with Novaled." Both, inversion and depletion OFETs are reported on by the group of scientists. Depletion OFETs with a high ON/OFF ratio are realized by keeping the doped layer as thin as possible, that is, a few nanometers only, which allows for a full depletion of the doped region by the applied gate voltage. Organic inversion transistors are facilitated by additional doping of the source and drain contact, which leads to efficient injection of charge carriers and allows for the creation of an inversion layer. We show that doping leads to a precise control of the threshold voltage of OFETs. Controlling and stabilizing the threshold voltage in OFETs is essential in the design and for the reliable production of larger integrated circuits. In particular, small and symmetric threshold voltages for p- and n-type transistors are needed for low-power complementary circuits.

Collaborators:
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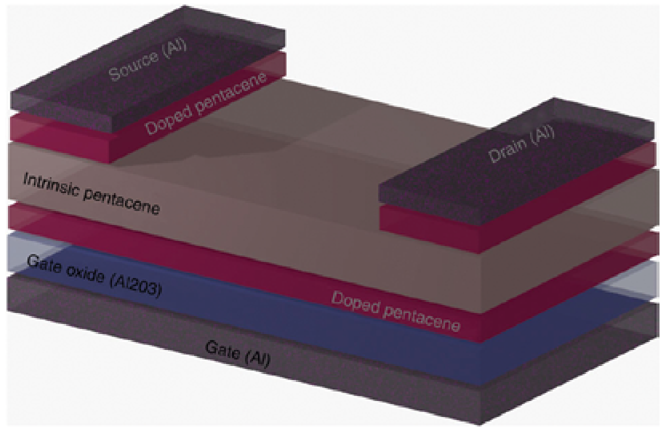
Institutions:
cfaed; TU Dresden

Path: Organic/Polymer

DOI: 10.1038/ncomms3775

Phys EE



Set-up of a transistor consisting of Al_2O_3 as gate oxide, a thin doped layer of pentacene as transistor channel, an intrinsic pentacene layer and doped source and drain contacts

Organic Permeable Base Transistor (OPBT)

Organic transistors are used, e.g., in flat panel or flexible displays, and sensor arrays. During the last years, switching devices with high on/off-ratios have been realized by the well-understood organic field-effect transistors (OFETs). However, further optimizations are required for high-frequency operation which are determined to a large degree by the channel length being the horizontal distance between source and drain contact. Advanced structuring methods for realizing short channels in the submicrometer range are necessary. Recently published techniques use lateral resolutions of 0.5–10 μm and show transit frequencies in the MHz range, but these approaches are neither suited for mass production on larger areas nor compatible with low-cost plastic electronics. With the objective of economic compatibility, the problems of high-resolution lateral structuring can be circumvented by alternative transistor setups with a vertical current flow where the short-channel structuring is related to the thickness of the organic semiconductor, precisely tunable in the nanometer range.

Method

The research group investigated a vertical transistor concept of organic permeable base transistors. An understanding of the operation mechanism of the device had to be developed, and applications for the transistor needed to be found. "In the vertical transistor concept, the current flows perpendicular to the substrate, a setup allowing for small channel lengths. The idea of the concept is that the current flowing between emitter and collector is controlled by a grid-like electrode (base) in the middle layer, therefore, the OPBT is similar to the vacuum tube triode but with semiconductor instead" explains Felix Kaschura. The resulting structure is a layer-by-layer concept ('sandwich structure') comprising three parallel electrodes. Thereby, the current can be controlled with the base potential. In between the electrodes an organic semiconductor is placed of the material such as e.g., C60 for n-type devices, and e.g., Pentacene for p-type devices. A combination of both, p-type and n-type is possible, and allows for complementary circuits. Doping of organic semiconductor can be easily applied to enhance charge carrier injection and improve performance. The openings are self-formed using postproduction annealing.

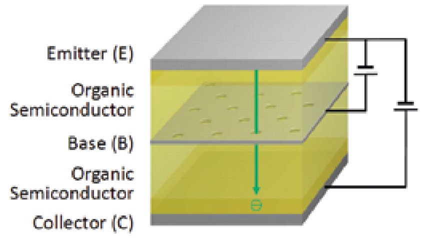
Results

An optimized vertical organic permeable-base transistor (OPBT) competing with the best organic field-effect transistors in performance, while employing low-cost fabrication techniques, has been presented. "Our approach does not only help to downscale the device but also demonstrates the route to a later device integration into larger circuits. Of course, insulating layers for structuring semiconductor devices are widely used. However, in the field of OPBTs issues arising from parasitic leakage, currents have not been considered yet, although the technique will be important for these devices, too" says Kaschura. The OPBT stands out by its excellent power efficiency at the highest frequencies. High on-state current density, switching speed, and current gain are achieved, while an inexpensive, low-resolution structuring technique is retained. It is also shown that an additional injection layer can easily be integrated at the emitter to reduce the contact resistance and to significantly improve the performance. The on/off ratio of C60 OPBTs is 10^6 and the differential current gain reaches a maximum of 2600, while Pentacene OPBTs do not achieve that performance yet (on/off 10^4, current gain 160).

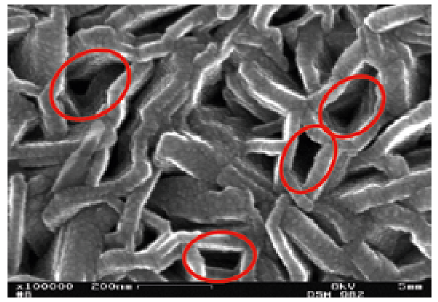
The results show the potential of vertical organic transistors. The transistor appears applicable in large-area and flexible electronics. It could be used as an OLED 'Driver in Display' applications, for fully organic and OLED-compatible processing. Also low power signal amplification, e.g., in sensor arrays, or a use in analog circuits, e.g., audio amplification or RFID-like communication are possible application fields. Finally, a demonstrator was built and presented at cfaed's Research Festival: An OPBT drives an Organic Light Emitting Diode, the OPBT itself is controlled by the signal of a solar cell which is used here as a light sensor.

Outlook

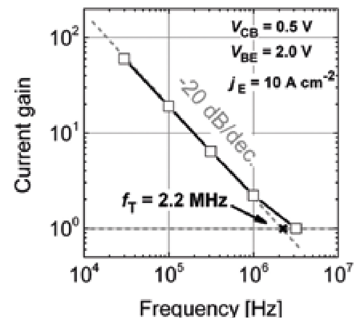
By replacing the Spiro-TTB with a better insulator, it is expected to reduce leakage currents and thus increase both, the on/off ratio as well as the current gain. The layer thickness of the intrinsic semiconductor will also be varied in order to tune the performance. Furthermore, drift-diffusion simulations of the OPBT will give a better insight into the device operation allowing to identify further optimizations.



The OPBT has a 'sandwich' architecture of 3 parallel electrodes (gray) separated by 2 semiconducting layers (yellow). The current flowing vertically can be controlled by varying the potential of the middle, permeable base electrode (B).



SEM image of the oxidized Aluminum base layer of a Pentacene OPBT. The base forms a network-like grid structure. Red circles show spots where large openings in the base layer can be formed.



Frequency performance of the C60-OBPT. The measurements have been performed at a fixed collector current bias of 4 mA (10 A cm^{-2}). The operation voltage is automatically adjusted by external circuitry and a V_{CE} of 2.5 V results due to a bias-stress effect.

Collaborators:
Frank Ellinger, Axel Fischer, Felix Kaschura, Bahman Kheradmand-Boroujeni, Karl Leo, et al.

Institutions:
cfaed; Kent State University; TU Dresden

Path: Organic/Polymer

DOIs:
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10.1063/1.4927478

Chem Phys EE

Polymeric Electronics: Fully Printed All-Polymer Ring Oscillator

Flexible, Functional and Wearable – The vision of shaping our future by developing the next generation of consumer electronics fascinates Tim Erdmann, PhD student within cfaed. Therefore, Tim's efforts are focused on the synthesis and optimization of semiconducting polymers (SCPs) for field-effect transistors (FETs) and are incorporated in a close collaboration with technology experts fabricating flexible and lightweight electronic devices by forward-looking low-cost and large-scale printing processes.

Scientific background

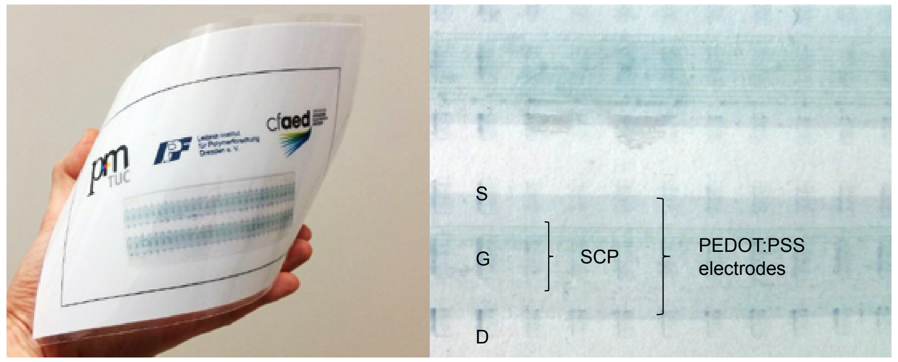
The ability of switching the current between two metal contacts was the absolute fundamental prerequisite paving the way for developing functional electronic circuits. Nowadays, we cannot imagine our world without electronic devices omnipresent in all areas of our life, such as medicine and healthcare, communication, transportation and entertainment. The most essential units in electronic devices are transistors providing the opportunity to control or to amplify electronic signals being of high importance in microelectronics. Thereby, the performance of the transistor is highly depending on the used semiconductor. Now, to enable the development of flexible, low-cost and functional organic-based electronics of the next generation, new semiconducting materials have to be developed to replace the rigid and comparably heavy silicon. For this purpose, conjugated polymers are one very promising class of materials additionally enabling the processability via modern low-cost printing technologies.

Polymer selection

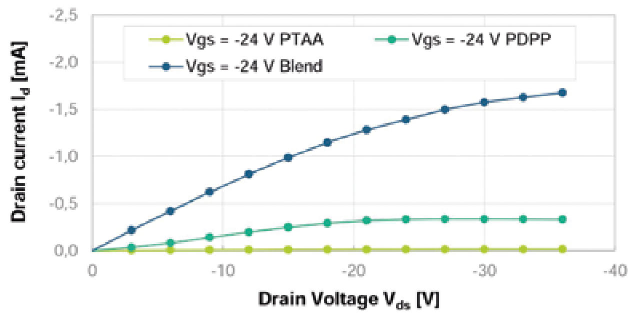
Tim focused on a class of high performance SCPs based on the diketopyrrolopyrrole (DPP) substructure also used as basic building block for popular pigments such as Pigment Red 254, commonly known as the "Ferrari Red". After solving synthetic challenges of this class of materials and synthesizing a series of conjugated DPP-based polymers via Stille coupling polycondensation, Prof. Dieter Neher (Uni Potsdam) and his group investigated the transistor performance. Dr. Riccardo di Pietro and Naixiang Wang from Uni Potsdam fabricated organic field-effect transistors (OFETs) on rigid glass substrates and investigated the transport properties. Charge carrier mobilities, the most crucial physical value of semiconductors for OFETs, higher than 1.4 cm^2/Vs were observed exceeding the performance of a comparable commercial material from Solarmer by more than 30 times. With these results, Tim analyzed the most promising polymer for continuing with the technology partners of Prof. Hübler's group from the Institute for Print and Media Technology of Chemnitz University of Technology (pmTUC).

Fully printed OFETs

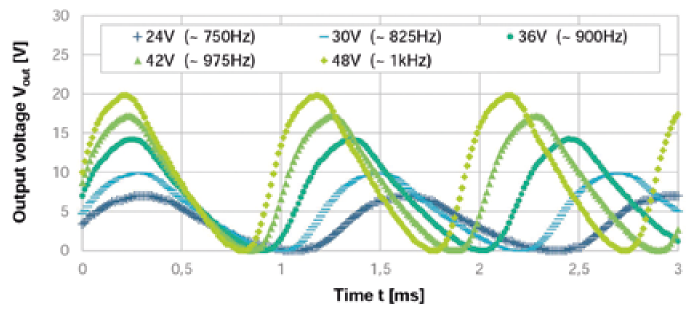
In a close collaboration with Dipl.-Ing. Daniel Höft of pmTUC, supervised by Dr.-Ing. Georg Schmidt, first all-polymer test OFETs were fabricated by spin-coating on polyethylenetherephthalate (PET) substrates equipped with prestructured poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT:PSS) source (S) and drain (D) electrodes. The fluorinated polymer CYTOP was used as low-k dielectric and PEDOT:PSS was printed to realize the gate electrode and the S/D contacts. The electrical measurements confirmed working OFETs, whereas the following work concentrated on realizing a good printability of the SCP. This was another main challenge because high performance SCPs tend to strongly aggregate in solution hindering a good printability, film-formation and reproducibility. Höft optimized the ink formulation by introducing new solvents and by blending the SCP with a well-soluble, low-performance polymer what improved the overall printing results and the OFET performance. Especially, the current in the on-state increased significantly by more than two orders of magnitude making this achievement promising for developing printed amplifier circuits. Lowering the effective concentration of active SCP was a successful compromise, but not the best way with regard to the composition of the semiconducting layer. Erdmann bypassed this by screening polymerization conditions. Replacing the initial powerful catalyst system for the Stille coupling polymerization with a less performing combination allowed access to SCPs with a lower range of molecular weight being much better soluble then before. Together with the new multi-layer dielectric approach from pmTUC, a new series of OFETs was successfully printed showing the same near record high charge carrier mobility of about 0.4 cm^2/Vs for fully printed and all-polymer OFETs.



Example of a laminated strip PET foil with two rows of printed all-polymer OFETs (left) and a magnified section (right). On top of prestructured interdigitating PEDOT:PSS electrodes (blue band) the semiconducting polymer (SCP) (green band), the dielectric (colorless) and source (S), drain (D) and gate (G) contacts (greyish) are imprinted successively.



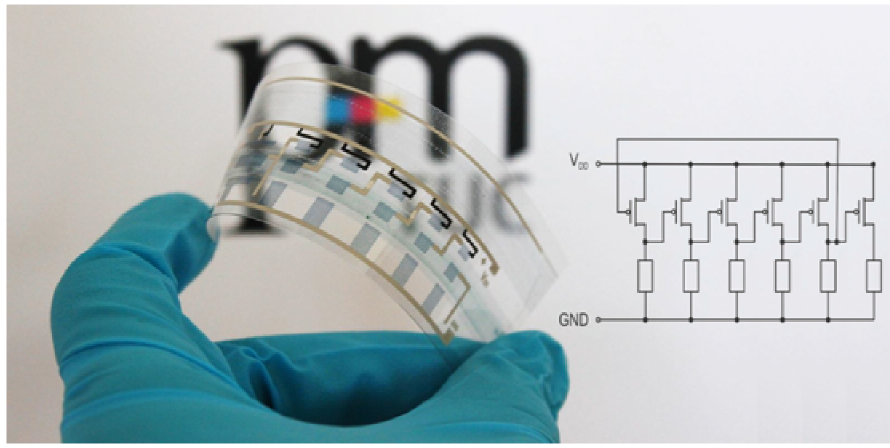
Collection of output curves of fully printed all-polymer OFETs at -24 V gate voltage with different materials as semiconductor: amorphous, well-soluble, low performance polymer (green), DPP-based polymer (turquois) and the blend (blue)



Oscillation of the fully printed all-polymer five-stage ring oscillator at different supply voltages

A big step up the ladder

Based on these great achievements, next efforts were focused on even more technologically challenging goals such as the fabrication of inverters. With the new optimized set of materials, it was not only possible to realize this aim, but additionally a well working five-stage ring oscillator was designed and successfully manufactured. The final successful fabrication of a fully printed and all-polymer ring oscillator, so far a non-reached highly challenging goal for DPP-based devices, is the result of a powerful collaboration between all involved scientists and one can look forward to even more important achievements for the next generation of consumer electronics within this unique collaboration.



Printed five-stage ring oscillator and its scheme of the electrical circuit including buffer stage

Collaborators:
Arved C. Hübler, Manfred Stamm, Anton Kiriy, Brigitte Voit, Daniel Höft, Georg Schmidt, Tim Erdmann

Institutions:
cfaed; TU Chemnitz; Leibniz IPF

Path: Organic/Polymer

Chem Phys EE

World's First Parallel Computer Based on Biomolecular Motors

Conventional computers have led to remarkable technological advances in the past decades, but their sequential nature – they process only one computational task at a time – prevents them from solving problems of combinatorial nature such as protein design and folding, and optimal network routing. This is because the number of calculations required to solve such problems grows exponentially with the size of the problem, rendering them intractable with sequential computing. Parallel computing approaches can tackle such problems, but the approaches developed so far have suffered from drawbacks that have made up-scaling and practical implementation very difficult. A study published in February 2016 in the Proceedings of the National Academy of Sciences (PNAS) reports a parallel-computing approach aiming to address these issues by combining well established nanofabrication technology with molecular motors which are highly energy efficient and inherently work in parallel.

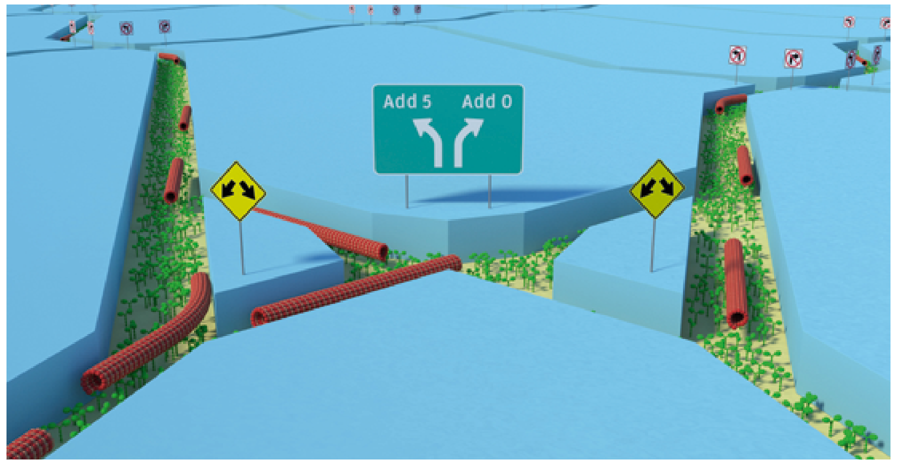


Fig. 1: Split junction overview. Illustration of protein filaments (red) propelled by molecular motors (green) arriving at a junction where they perform a calculation operation (adding 5 or adding 0).

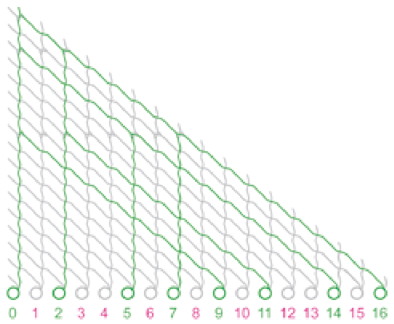


Fig. 2a: Encoding of the combinatorial Subset Sum Problem into a lithographically defined network of nanoscale channels – green numbers label the problem's solutions at the network's exits.

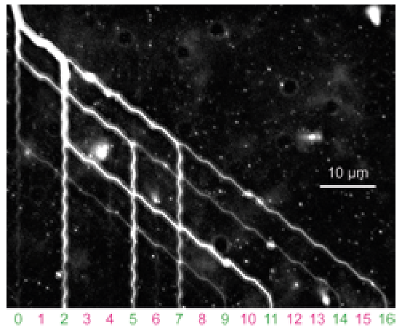


Fig. 2b: Accumulated paths of protein filaments exploring the network in a massively parallel fashion to arrive to the problem's solution.

A revolutionary approach

The study reports a fundamentally new approach based on a combination of nanotechnology and biology that can solve combinatorial problems. It is scalable, error-tolerant, energy-efficient, and can be implemented with existing technologies. The pioneering achievement was developed by an international consortium of researchers around the cfaed scientists Prof. Stefan Diez and Dr. Till Korten. They realized a parallel computer based on designed nanofabricated channels explored by protein filaments in a massively parallel fashion. The filaments are propelled by molecular motors. The researchers selected a benchmark combinatorial problem that is notoriously hard to solve with sequential computers, and 'encoded' its solution into a network of nanoscale channels (fig. 2a) which was produced using e-beam lithography, a well-known chip-manufacturing technique. This network then is explored in parallel by many protein filaments (here actin filaments, fig. 2b, or microtubules) that are self-propelled by a molecular layer of motor proteins (here myosin or kinesin) covering the bottom of the channels. The design of the network automatically guides the filaments to the correct solutions of the problem. This is realized by different types of junctions, causing the filaments to behave in two different ways. As the filaments are rather rigid structures, turning to the left or right is only possible for certain angles of the crossing channels. By defining these options ('pass junctions', not shown and 'split junctions', fig. 1) the scientists achieved an 'intelligent' network giving the filaments the opportunity either to cross only straight or to decide between two possible channels with a 50/50 probability.

Results

The time to solve combinatorial problems of size N using this parallel-computing approach scales approximately as N^2, which is a dramatic improvement over the exponential (2^N) time scales required by conventional, sequential computers. The approach is scalable with existing technologies and uses orders of magnitude less energy than conventional computers, thus circumventing the heating issues that are currently limiting the performance of conventional computing. A proof-of-concept demonstration is provided of such a device by solving, in a parallel fashion, the small instance of the subset sum problem, which is a benchmark NP-complete problem.

Collaborators:
Stefan Diez, Till Korten, et al.

Institutions:
cfaed; B CUBE; University of California; Linnaeus University; University of Liverpool; Lund University; MPI CBG; McGill University; Molecular Sense, Ltd.; Philips Research and Philips Innovation Services; TU Dresden

Path: CIP

DOI: 10.1073/pnas.1510825113

Bio Phys EE

High Frequency Characterization of DNA Structures

There is a certain desire to characterize materials used in applications such as mobile communications working in the higher radio frequency range. The electrical parameters of these materials need to be known to be able to simulate the desired applications. The most interesting parameters are the wave propagation effects as well as the related losses. In this project, the group aims at developing and optimizing a characterization platform, which enables material characterization and determination of the mentioned parameters in the radio frequency range up to a few hundred GHz. Up to today, there are little to no methods known which allow for such a broadband material characterization, especially related to on-chip applications (e.g., silicon-based) in planar technology or simple substrate materials. In the medium-term, the aim is to characterize not only solid material samples, but liquids as well. This is necessary to characterize the influence of DNA Origami on the electrical parameters of a system, where they could be incorporated as single devices or even as part of the overall material platform. The idea is to investigate if and how DNA Origami can influence the behavior of the material, when altered e.g., in shape, size, concentration or metallization.

Method

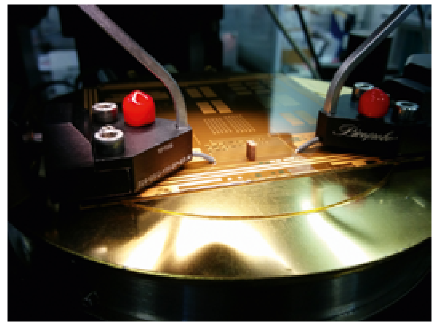
To achieve the desired results, Patrick Seiler uses on-wafer radio frequency probes for measurement with a network analyzer. On-wafer probes are realized by three very small pins that can be pushed on the top of a planar substrate to contact planar devices. With this setting, the young scientist is able to measure devices on top of the substrate layer, usually on chips or printed circuit boards. Of course, such a specialized approach means to deal with some specific constraints: handling and exact placement of the very small-sized objects as well as measurement problems in the high frequency range. Since it is not possible to do measurements only with network analyzers here, specialized mixers are necessary to push the frequencies to the desired measurement band. The result is a rather bulky setup of hardware, which needs to be managed properly during measurement. Until now, Seiler already was able to characterize a whole range of solid materials such as plastics, ceramics, and even some kind of wood. This alone already represents a big achievement, because there are no alternative measurement methods with such constraints on measurement sample size and the overall procedure concerning the very high measurement frequencies and bandwidth. Seiler's approach allows the characterization of nearly any dielectric solid material in a very easy and broadband manner. The overall goal is to find mathematical methods and procedures enabling characterization of substrate materials for a very broad frequency range. The characterization platform is the foundation for the targeted measurements of DNA Origami and possibly other 'unknown' materials. Thus, Seiler is modifying the already proven setup, which was developed for solid materials. To measure liquid materials, he uses the same substrate which is complemented now by applying a kind of liquid material channel on top of the known substrate. "We expect that the methods we used for solid materials will work with the liquids, too", Seiler explains. With today's methods, DNA origami can only be measured within a solution. The process is to compare the results of a test series with and without origami in the carrier solution. The identified differences provide a glimpse of the electrical properties of DNA origami. "One of the most interesting parameters is called permittivity. It consists of a 'real part' describing how electrical waves propagate through a medium and an 'imaginary part', which accounts for the losses inside the media", Seiler explains. A few parameters of DNA origami are expected to change the electrical behavior of the carrier solution: the origami concentration, the size, and the shape of a single DNA origami. In summer 2015, the fabrication of the DNA origami started, and first measurements took place at the end of the year.

Outlook

In the near future, the measurement platform will be used to fully characterize liquid materials as well. To extend the setup for solid materials to liquids in general, the calibration has to be adjusted. This investigation started in early 2016. Additionally, the setup will be extended to even higher frequencies such as 500GHz.

Networked Research

Seiler is fascinated by the Cluster's cross-disciplinary approach: "The large networked structure of cfaed provides many connections that I would not have as a sole PhD student working on a narrower topic. I receive the DNA origami from the BAC path and work closely together with chemists. Of course, some processes take more time and the communication and management effort is higher. But I consider these cons-at-first-glance as benefits: the working style at cfaed is closer to the one in industry, and you gain more out of it for your personal development. You are not doing only scientific work all day long, but also have to take care of lots of organizational issues and other things, such as communicating and scheduling work with others or writing papers or proposals and presenting yourself. This gives you a better perspective of work in general", Seiler sums up.



On-wafer probes contacting a planar transmission line for the measurement of the electrical parameters of a plastic sample on a polyimide substrate from 140 to 220 GHz.

Collaborators:
Patrick Seiler, Bernhard Klein, Niels Neumann, Dirk Plettemeier, Franziska Fischer, Mathias Lakatos

Institutions:
cfaed; TU Dresden

Path: BAC

DOI: 10.1109/MMS.2015.7375461

Chem CompSc EE

Towards Electronic Nanodevices by Arranging Conjugated Polymers on DNA Origami

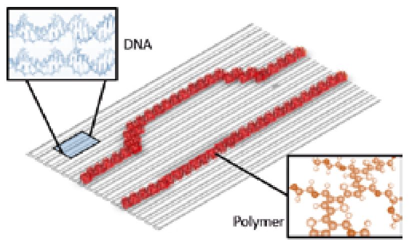
In a biologically inspired approach, the BAC Path develops complex, DNA-based templates for the bottom-up synthesis of hybrid structures for transmitting, switching and amplifying electronic and/or optical signals.
The scientists work on novel synthesis routes that allow building functionality into engineered 2D and 3D DNA origami structures by attachment of nanoparticles, conjugated polymers or fluorescent dyes with an almost unprecedented site-specificity. The goal is to build up functional devices like transistors or nano-antennas out of these structures with the aim that these can be integrated into nanoelectronic or nanooptic circuits in future. Franziska Fischer investigates the site-specific integration of conjugated polymer molecules.

Method

The specific feature of DNA is the ability to form double-stranded helices. If the sequences of two single strands match, they will bind and form a double strand. Since Nadrian Seeman introduced DNA nanotechnology in the early 1980s, scientists have developed methods that use this principle to not only form double strands but even more complex 2D and 3D shapes. The method applied in the BAC Path is the aforementioned 'DNA origami' where DNA is being weaved into a piece of 'fabric': one long DNA single strand runs through each piece in parallel lanes and gets interwoven with short DNA strands. The short strands are called staples. The sequences of the staples and parts of the long strand match, just as in the double strand. Therefore, staples and long strand bind, which folds the long strand into place. The result is the desired DNA template. The weaving is done by the DNA itself during a heating and cooling process in solution. The processing time depends on the desired object – 2D structures can be synthesized within two hours, for 3D structures it takes between a day and a week. The fabricated templates can be considered as 'breadboards'. "We aim at 'pinning' the particles exactly at the desired positions within the structure. In one microliter you can have over 2 billion of theses templates. The template formation is self-driven (based on self-assembly) and so is the nanoparticle placement. Therefore, this approach could be a way to produce devices in a highly parallel fashion – and very energy-efficient, and straightforward." Fischer explains.

How to place the nano-objects correctly?

The exact placing is organized with the help of the staples. Every staple fits exactly into one position in the DNA template. By making the staples longer, i.e., adding parts that are not woven into the template, the scientists create specific sections that can serve as free anchor points. The nanoparticles have DNA attached that binds to these anchor points, again using the double-strand formation-principle. The active particles investigated in the BAC Path are e.g., gold, quantum dots or conjugated polymer molecules.



Scheme of a rectangular DNA origami template decorated with conjugated polymer molecules along designated paths

Fischer investigates the conjugated polymers. 'Conjugated' refers to a feature in each polymer chain that, in contrast to the majority of polymers, allows charge carrier movement. Therefore, under certain conditions, these polymers can conduct electricity. Fischer's topic is basic research. One major question was how to combine the water-based DNA chemistry and the hydrophobic polymers; another was how to bind DNA to the polymer molecules to anchor it on the DNA template just like the other nanoparticles. Fischer and her collaborators on this project at the Leibniz IPF decided to custom-synthesize a polymer that meets both demands. Adapting, extending, and fine-tuning the synthesis protocol took no less than one year of work, but finally, the scientists succeeded in coupling the polymers to the DNA origami.

Outlook

The ongoing work aims at improving parameters such as the yield or the reproducibility in the first place. Then, a major topic will be building more complex hybrids, with not just polymer but also other nanoparticles on the template, and the characterization of the hybrids. Fischer says: "We have shown that we can manipulate the polymers on the single-molecule level. Now we want to use these new building blocks in origami and find out how it can contribute best to our goals in the Path. One far goal of my colleagues is for example to build antennas for optical devices, which is currently done by lithography. We think that DNA origami could complement lithography-based nanofabrication someday as new energy-efficient, less time consuming, entirely parallel component." One more argument for this is that the evolution of electronics technology seems to focus more and more on 3D structures. DNA origami on the other hand can easily cast 3D structures what makes them even more thrilling.
Based on the positive results achieved during the first two years of the Cluster, in the second period the group will put more focus on applied research connected with the integration of self-organized components into electronic and/ or optoelectronic devices. In this context, they combine advanced top-down and bottom-up methods for a controlled deposition of DNA-based hybrid structures into arrays on surfaces. Fischer's work will probably contribute here, since polymers shall play a role in the origami placement.

Collaborators:
Franziska Fischer, Anja Henning-Knechtel, Anton Kiriy, Michael Mertig, Johanna Zessin, Dirk Plettemeier, Patrick Seiler

Institutions:
cfaed; KSI Meinsberg; Leibniz IPF; TU Dresden

Path: BAC

DOI: 10.1002/pssa.201431931

Chem Phys EE

Towards DNA-Based Plasmonic Waveguides

The Biomolecular-Assembled Circuits Path (BAC) of cfaed is creating novel self-assembled devices from non-CMOS materials such as metallic or semiconducting nanoparticles, polymers or organic molecules on DNA nanostructures that shall transmit, switch or amplify either optical or electronical signals. In contrast to conventional electronic components, billions of copies self-assemble in a drop of water without the need for expensive, sophisticated machines or fabrication facilities. The group of Dr. Thorsten-Lars Schmidt develops DNA-based plasmonic waveguides that could guide light through structures that are much smaller than the wavelength of light and may enable optical short-range on-chip or inter-chip communication.

High-precision game: guiding light by plasmonic waveguides

DNA origami is a technique to create almost arbitrary two- and three-dimensional shapes out of synthetic DNA, which is chemically the same material used by nature to store biological information. Using the programmable Watson-Crick base complementarity of two DNA sequences, functional materials such as metal or semiconducting nanoparticles can be arranged with nanometer precision on DNA origami scaffolds. A main goal of Schmidt's lab is the self-assembly of plasmonic waveguides using gold nanoparticles arranged on a DNA origami template. If one end of such a waveguide is irradiated, for example by a laser, the light pulse can propagate through this structure, which is many thousand times smaller than conventional glass fibers. These dimensions are therefore compatible with nanometer-sized microelectronic components and novel DNA-based devices could potentially be integrated to facilitate optical near-field communication on or between chips. In such waveguides, each gold nanoparticle needs to bind to its designated binding site and its position needs to be precisely confined in three dimensions, as the absence of a single gold nanoparticle can destroy the functionality of the entire waveguide. If, for example, the attachment yield for each particle in a waveguide precursor consisting of eight nanoparticles is 80 %, only 17 % (= $0{,}8^8$) of the waveguide precursors are complete and functional. In a comprehensive study, several synthesis parameters were optimized to yield an unprecedented particle coupling yield of 98,7 % (fig. 1).

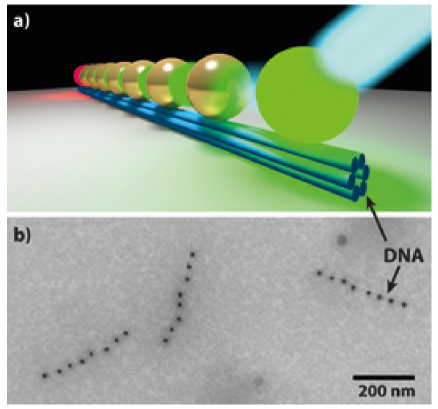


Fig. 1: DNA-based self-assembled plasmonic waveguides. a) Artistic representation; b) Electron micrograph of waveguide precursors consisting of gold nanoparticles on a DNA scaffold

Triangulating the double-strand

In a second project, triangulated DNA origami structures were designed and synthesized (M. Matthies et al., Nano Letters 2016). In the macroscopic world, triangulated construction elements are used, wherever stiff and material-efficient structures are needed (high-voltage power lines, construction cranes, Eiffel tower...). However, most DNA origami structures consist of parallel DNA helices, which is very material-inefficient. To construct triangulated structures such as the one in Figure 2, a custom-written software was developed. Other than the standard 6-helix bundles (fig. 1), these structures have well-defined cavities at regular distances. These shall next be filled with gold nanoparticles to create an alternative plasmonic waveguides design with a better particle confinement.

Collaborators:
Thorsten-Lars Schmidt, Stefan Diez, Alexander Eychmüller, Andreas Fery, Nayan P. Agarwal, Michael Matthies, Michael Mertig

Institutions:
cfaed; Fraunhofer IZI; HZDR; Leibniz IPF; BIOTEC; TU Dresden

Path: BAC

DOI: 10.1021/acs.nanolett.6b00381

Chem Phys

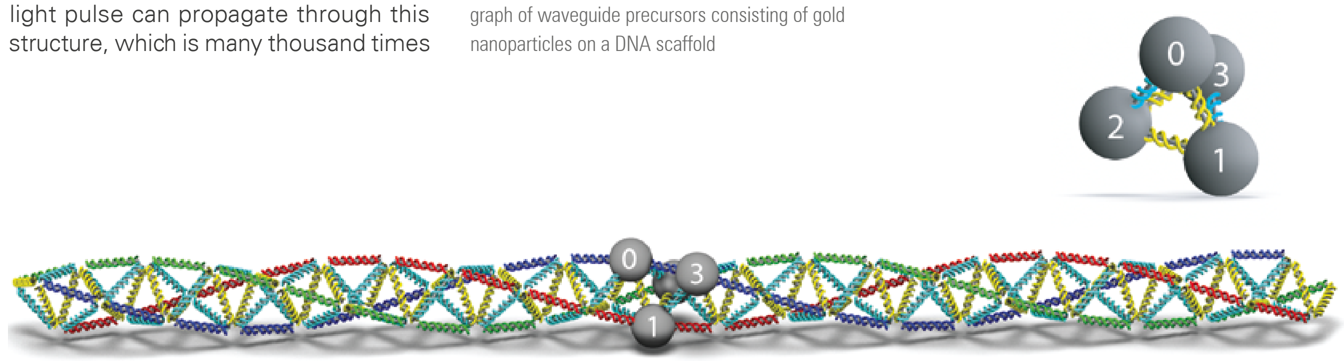


Fig. 2: Computer model of a tetrahedral truss
Top right: Repeating tetrahedral unit

Chemical Logic Circuits

Martin Elstner's work focuses on the implementation of information processing by chemical species. This means, that analog to today's electronic based computers, chemicals (molecules, ions, polymers) can act as information carriers and chemical reactions can process this information. A realization of this abstract concept is possible by chemical logic gates, molecules that transform input signals to defined output signals. Interestingly, (bio)chemical reactions allow the easy construction of an IMP logic gate (implication logic), which is very hard to construct by classic electronic elements. This logic gate displays some very powerful properties such as computational completeness. This means that any logic equation can be transformed to IMP logic.

Method

The group heavily uses IMP logic that takes sugar molecules as input signals, and therefore calls their computer the 'sugar computer'. Sugars are important substances in biological cells, a so-called 'biofuel' and also important for information storage in DNA. Since their computing scheme can act on biological inputs, it is not seen as a competitor to electronic computers but as a possibility to augment established processes. This means, that some parts of a computation can be done chemically (e.g., the first steps for massive parallel data acquisition) followed by classical electronic computations. The major advancement of this methodology is that computation is possible in areas that cannot be reached by silicon microchips. 'Wet computing' could be done inside cells and agglomerated data transmitted out.

Challenges

Major challenges are the combination of several logic operations on a molecular level to ensure a proper execution of programs. As a first milestone, Elstner enabled a liquid handling system to organize the information flow between chemical logic gates. The scientists around Elstner rely on open hardware technology to conduct their experiments and the use 3D-printed equipment. They also bring new designs to the community via their github account on github.com/MartinEls. The first examples of molecular computing include a 4-bit adder circuit, a very basic element for number representations. To have some fun after the hard work in the lab, the scientists have implemented a sugar-based version of the children's game 'tic-tac-toe'.

Outlook

Ongoing research focuses now mainly on microfluidics for spatial control of the elements. This also includes 3D-printing techniques or paper-based approaches for quick and low-cost manufacturing of prototypes. It is Elstner's strong believe that easy-to-adopt technologies are required to bring molecular information processing to the application stage. He also focuses on the interface of chemical and electronic devices. For a useful machine, the result of a chemical calculation has to be fed into an electronic counterpart for further processing. Furthermore, some control features of the electronic circuit over the chemical reactions is desired. For instance, Elstner's group uses electronic heating to trigger a chemical reaction that is the starting point of a logic cascade.

In summary, Elstner's work will strongly contribute to the development of chemical sensors for analytical applications. He aims at linking them to electronics to combine the best features of both worlds.

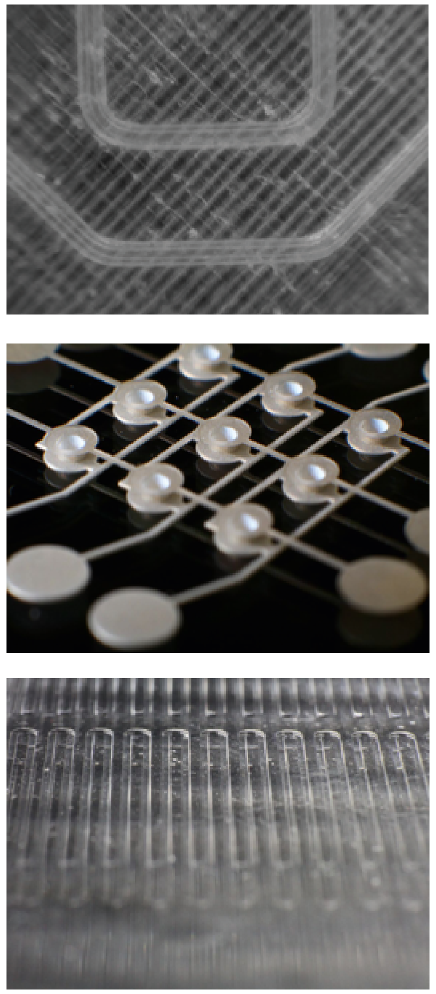
Collaborators:
Martin Elstner, Alexander Schiller

Institutions:
cfaed; Friedrich Schiller University Jena

Path: CIP

DOI: 10.1021/acs.jcim.5b00324

Chem



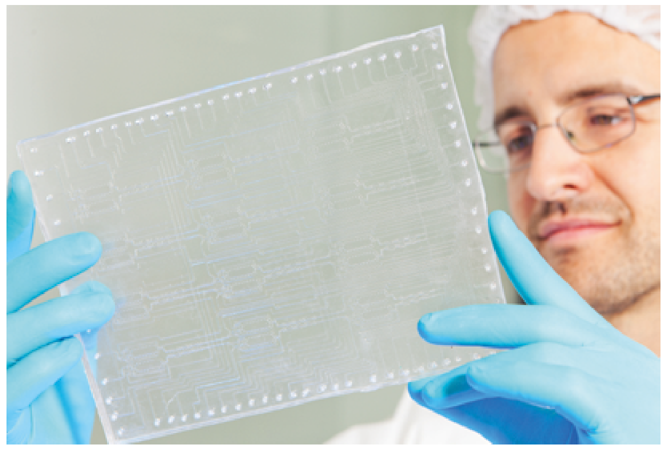
Microfluidic channels for spatial and temporal control of logic functions generated by rapid manufacturing technologies. High integration circuits need layered structures and well defined channel shapes.

Fluidic Microchemomechanical Integrated Circuits Processing Chemical Information

Lab-on-a-chip (LOC) technology has blossomed into a major new technology fundamentally influencing life and natural sciences. Here, the group of scientists presented the concept of a microfluidic central processing unit which combines both, control and execution units and, moreover, the complete power supply on a single chip and introduces the decision-making ability regarding chemical information into fluidic integrated circuits. Consequently, this system is able to process chemical information completely in a self-controlled manner and is energetically self-sustaining.

Method

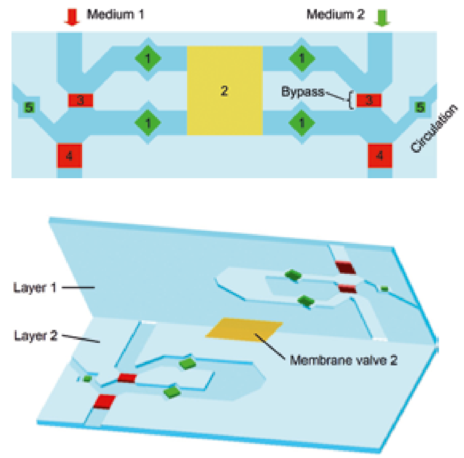
George Whitesides, a visionary in microfluidics, recapitulated in 2010 that the expected revolution of LOC technology has not yet happened. Why? Looking at the LOC state of the art, there are a lot of small fluidic chips for nearly every purpose. But what is missing: The big devices to control them. Basically, to run a LOC at least an external sensing and control system and of course a power supply are needed. Compared to common lab equipment, this offers no functional advantage. To overcome this, the group of Prof. Andreas Richter adapts principles of computer system architecture to LOC technology. Basically it integrates the control and sensing system directly on the fluidic chip. But how can that be done? With intelligent materials! Special polymers are used which have the ability to make decisions and hence are able to control complex processes directly on the chip.



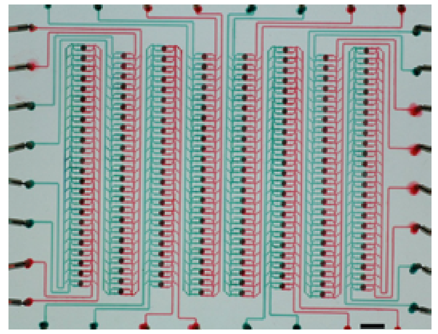
Fluidic microprocessor

Results

The development of 'smart' polymer-based components such as opening and closing valves enables building complex fluidic chips for a broad variety of applications. An example is a microchip for equidistant long-term investigations. It consists of 192 serial connected cascades, each able to carry out a defined mixing reaction for continuous parameter monitoring. One cascade works in principle in three repetitive steps: 1) metering of the reagents, 2) mixing, and 3) activating the next cascade. This protocol follows an exactly defined time schedule. But what is the big deal? All the 2096 integrated microvalves do not need any external power supply or electrical control signal! They are making their decisions by processing chemical information. This unique approach allows the development of LOCs, where decisions are made directly on the fluidic chip. For future systems more complex components like chemical fluidic transistors, logic gates, flip-flops and oscillators are being developed. The combination of these elements allows to create fluidic systems with a new level of complexity. To predict their behavior and to make the design process more efficient, an electronic design automation (EDA) software was adapted for microelectronic circuit design for the group's requirements in microfluidic system development. Both, the EDA software and the fluidic system approach, enables the development of a completely new generation of LOC devices.



Schematic of a mixing cascade with opening valves (red), closing valves (green) and a membrane valve (yellow) between two fluidic layers



Fluidic microprocessor for equidistant long-term investigations. The different channels are filled with food colouring.

Collaborators:
Andreas Richter, Merle Allerdissen, Andreas Voigt, et al.

Institutions:
cfaed; TU Dresden

Path: CIP

DOI: 10.1039/C2LC40617A

Chem EE

Microkernel-Based System for Heterogeneous Manycores

M3 is a microkernel-based operating system that aims at supporting the next generation of wildly heterogeneous systems based on a hardware/operating-system co-design.
The key idea is to add a small hardware component next to every core as your interface to abstract the heterogeneity of the cores. This hardware component is called a data transfer unit (DTU) and offers message passing and remote memory access. Otherwise, no assumptions are made about the features that a core provides, so that different kind of cores can be used to accelerate specific workloads or lower their energy requirements. All cores are thereby treated as first-class citizens, i.e., untrusted code can run on all cores and operating-system services such as filesystems or network stacks are accessible from all cores.

The M3 Design

The recent past has already seen a steady increase in the number of cores found in systems of any size. Together with the trend to very heterogeneous systems and the promise of cfaed for even more exotic components, the question arises how to program these kinds of systems. Current operating systems (OSes) run the same kernel on all cores they manage and rely on specific hardware features such as a privileged mode, exceptions, and a memory management unit. Although these features could be provided for some special-purpose cores, it would entail a significant cost for porting the kernel to each of the architectures or for implementing a common architecture on them. For other components like FPGAs, it would be even more difficult. The design of current systems must be rethought, both in terms of hardware and software. The team's design allows to integrate arbitrary cores as first-class citizens in the system. To achieve that, as shown in the figure, existing cores are not modified, but a DTU is added next to each core. All cores and memories are connected via a package-switched network-on-chip (NoC) as the common fabric for communication. The combination of a core, its memory (cache or scratchpad memory) and a DTU represents one element in the NoC, called processing element (PE). As very heterogeneous PEs must be supported, the OS design runs the kernel on one or more dedicated PEs without applications on these PEs. Instead, applications are run on the other PEs, directly on bare-metal. To enforce isolation, the kernel controls the DTUs of the application PEs remotely, because PE-external resources can only be accessed via the DTU. The PE-internal core and memory can be used by the application without restriction. This concept is called NoC-level isolation. Similarly, OS services are provided at NoC-level. For example, to access files, an application communicates with the PE, that currently runs the filesystem service. Similar to traditional OSes, the M3 kernel is the privileged component in the system. As such, it decides who can communicate with whom. Therefore, the kernel is the only component that can establish communication channels to other cores or memories. The applications can only use these channels. The M3 kernel is designed as a microkernel, which means that it only provides the necessary mechanisms to implement the majority of the OS (network stacks, filesystems, drivers, ...) outside of the kernel. Furthermore, unlike traditional microkernels, applications can directly communicate with each other through the established channels without kernel involvement. This eliminates a large part of the costs traditionally associated with the microkernel design.

First Results

M3 is currently running on the Tomahawk2 chip, the simulator for the next generation of Tomahawk, Linux (by using it as a virtual machine) and gem5. It is available as open source at https://github.com/TUD-OS/M3. The first results are promising, showing that the existing implementation can even outperform Linux in some benchmarks by more than a factor of five even without exploiting specialized accelerators.

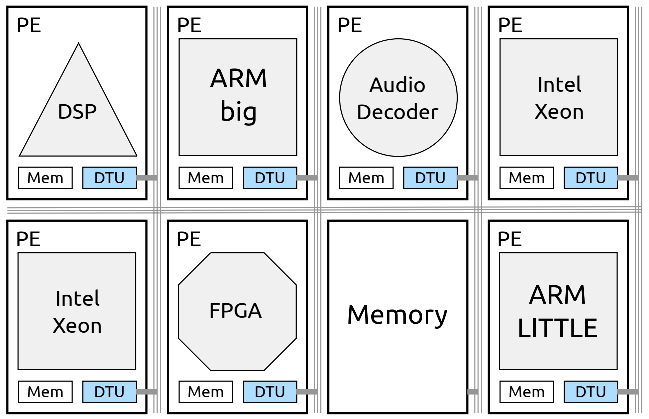
Collaborators:
Nils Asmussen, Hermann Härtig, Gerhard Fettweis, Benedikt Nöthen, Marcus Völp

Institutions:
cfaed; TU Dresden

Path: Orchestration

DOI: 10.1145/2872362.2872371

CompSc EE



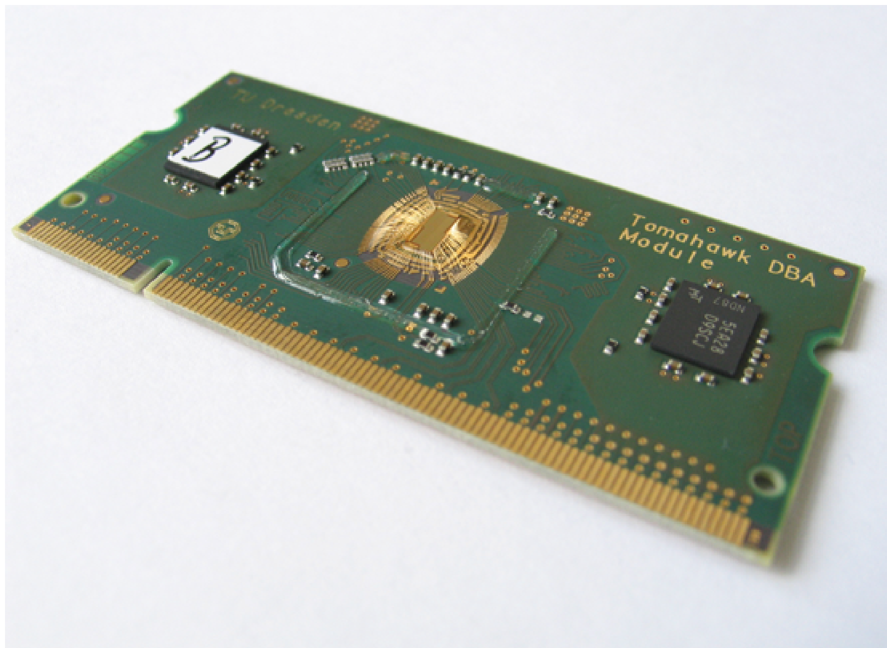
The vision of M3: integrating very heterogeneous cores into one system by adding a DTU to each PE

NoC Level: Ultra Low Power Transceiver

With the increasing complexity of modern multi-processor systems-on-chip (MPSoCs), the optimization of the on-chip interconnect fabric (Network-on-Chip – NoC) can significantly improve system performance in terms of data throughput and energy efficiency. This especially holds for heterogeneous MPSoCs with different types of compute cores, as for example the Tomahawk chips developed within cfaed. NoCs contain point-to-point links (network channels) between cores and routers. Especially for larger chips and hierarchical NoC architectures, the physical length of these interconnects can be in the range of some mm. This provides challenges for link design and implementation to achieve high data throughput at low energy per bit and small area overhead. In this work, which started within the Leading-Edge Cluster CoolSilicon and successfully continued within cfaed, novel serial links for NoCs have been developed. Target applications are energy efficient data transmission on Systems-on-Chips (SoC) (e.g., for 5G mobile communication applications) over some millimeter physical distance at minimum area and power overhead.

Method

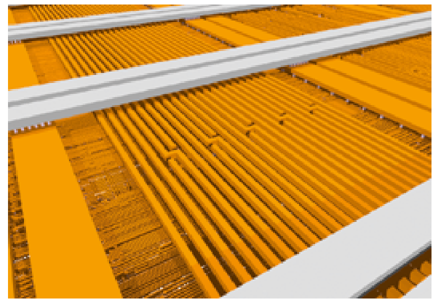
Typical NoC communication scenarios are considered, where idle phases without payload data transfers occur. Therefore, an innovative completely stoppable clocking architecture has been developed in which the NoC link is only clocked when payload data is to be transmitted. Thereby this link does not consume static idle power. The figure of merit useful energy per bit has been introduced. This work reduced the energy demand per useful bit by a factor of 4 compared to the state of the art to less than 65fJ/bit/mm for the complete transceiver. This leads to a significantly increased energy efficiency of systems which power consumption is dominated by digital signal processing, as for example 4G/5G base stations. This NoC Link has been successfully implemented in 65nm and 28nm CMOS technology with up to 90GBit/s over 6mm on-chip interconnect which proves scalability of the proposed approach. This work has been published in the world's top circuit design conference ISSCC 2012 and in the world's leading IEEE Journal of Solid-State Circuits in 2015. In addition, it received the 'Cool Award 2015' of the CoolSilicon Leading-Edge Cluster.



Tomahawk3 module

Result

As the first complete realization of a serial NoC link, this approach allows seamless integration into NoC realizations for various applications. The serial NoC links have been successfully implemented on three MPSoCs (Tomahawk2 – 65nm, Tomahawk3 – 28nm, Tomahawk – 28nm), which have been developed in cooperation with Prof. Fettweis' Vodafone Chair Mobile Communications Systems.



Serial NoC Link Routing in the upper layers of the chip metalization

Collaborators:
Sebastian Höppner, Dennis Walter, Thomas Hocker, Stephan Henker, Stefan Hänzsche, Daniel Sausner, Georg Ellguth, Jens-Uwe Schlüßler, Holger Eisenreich, René Schüffny, Gerhard Fettweis, Christian Mayr

Institutions:
cfaed; TU Dresden

Path: Resilience

DOI: 10.1109/JSSC.2014.2381637

CompSc EE

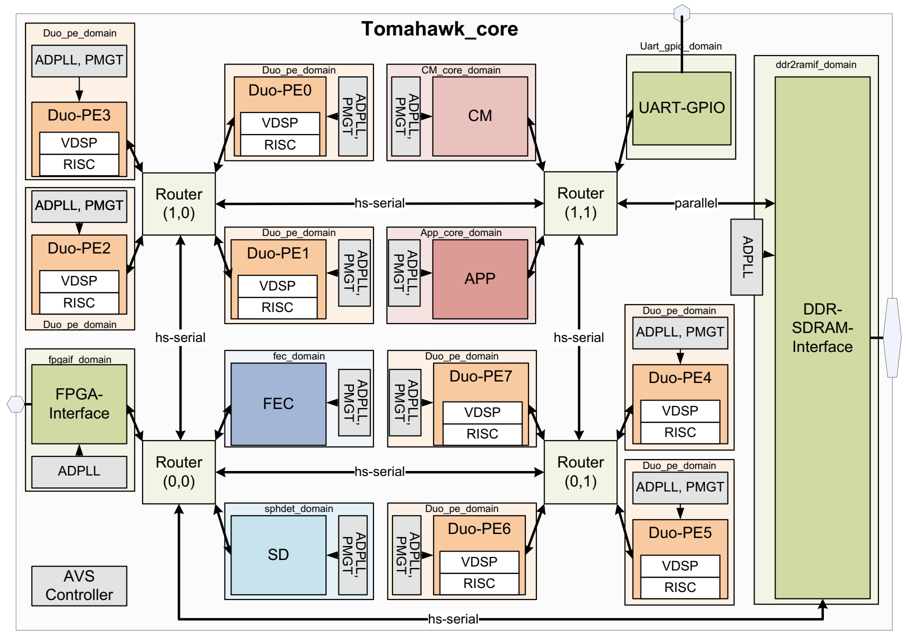
The Tomahawk Platform: A Heterogeneous Multi-Processor System-on-Chip (MPSoC)

Following the introduction of the disruptive 5th generation mobile communications network (5G), many novel applications – and requirements – appear on the horizon. To meet these requirements, an entirely new hardware and software approach is needed. Mobile devices will consist of significantly improved components. The Tomahawk2, the second chip generation exploiting the Tomahawk platform, is a research chip to implement and test a whole set of ideas regarding this mobile revolution. In general, the term 'Heterogeneous Multiprocessor System On-chip' describes a chip that consists of multiple processors, but in difference to a standard multicore CPU, a multiprocessor comprises different types of processors on one chip. The Tomahawk chip family is developed for testing, characterizing, and analyzing. Those approaches that prove good performances later might be taken out and used by industry for future chips, e.g., in mobile devices.

Method

To match the 5G requirements outstanding performances, highly energy-efficient systems are needed. Parallelization can be one approach to increase performance while saving space and energy. Another way is the implementation of application-specific instruction set processors (ASIPs) to reach better performances and drastically decrease energy consumption. The Tomahawk2 combines these approaches. It consists of 20 processing units all connected by a network-on-chip with high-speed serial links. The application processor executes the actual application and defines tasks for parallel execution. The engineers use a specific programming language based on C – it is named 'TaskC Programming Model' and was also developed by the hardware group of Prof. Gerhard Fettweis. Another core serves a CoreManager which schedules the tasks for the processing units. The processing work is done by eight general-purpose processors and eight vector DSPs. A DSP is a specialized microprocessor, with its architecture optimized for the operational needs of digital signal processing. And finally, there are two application-specific circuits: an FEC (Forward Error Correction Core) and a Sphere Detector, which are used for the signal decoding in MIMO systems (multiple-input and multiple-output is a method for multiplying the capacity of a radio link to exploit multipath propagation) with multiple antennas at transmitter and receiver side.

Besides this highly specialized architecture, trickier features were implemented on the chip. The supply voltages and clock frequencies can be changed dynamically and thereby the processing can adapt to the respective application, according to the number of scheduled tasks. For a typical mobile communications LTE application, Tomahawk2 consumes around 500mW. Comparable state-of-the-art platforms require an order of magnitude higher power consumption while serving the same performance.



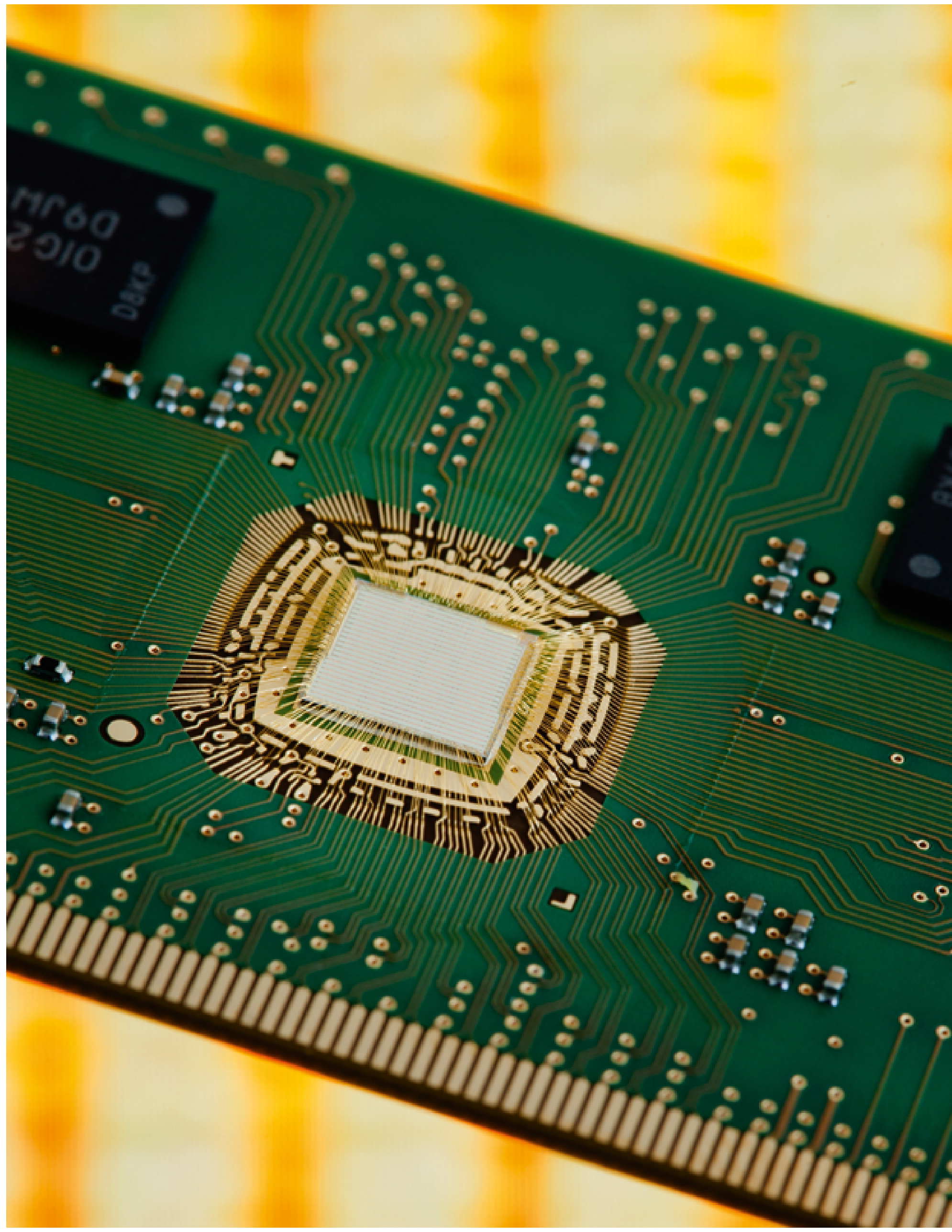
Block diagram of the Tomahawk2 MPSoC

Outlook

Such heterogeneous systems are currently at the development stage and not yet used in today's applications. In future, over a period of around 5-10 years, architectures like presented here will be used for chips that could run nearly everywhere, especially on smartphones and other mobile devices. They also can be implemented, e.g., in cars, but they have special prejudices in those environments where little energy may be consumed. The chips could also be connected to build up a network which will enable them to work as a base station for mobile communications, for instance. The next technical achievements should enable these features. Fettweis outlines the near-future development: "The upcoming Tomahawk generations again will be subject to many changes. First, our target technology is the 28nm super low-power process by Globalfoundries that enables 2x more power savings than the 65nm technology used for . For example, the Tomahawk3 which came back from Globalfoundries in Fall 2015 implements some application-specific processors exhilarating fundamental database algorithms. It forms the next step towards supporting the performances for Mobile Edge Clouds. Now, Tomahawk4 combines the applications of databases and mobile communications systems. Besides the Tensilica cores from Cadence, we will use ARM processors. Unlike Tomahawk2, the Tomahawk4 carries processing elements that are all equipped with special features for intelligent data and memory management."

Networked research

The Tomahawk would not exist without the working partnerships at several levels. Main developers are the hardware group of the Vodafone Chair Mobile Communications Systems and the Chair for Highly-Parallel VLSI-Systems and Neuromorphic Circuits, both of TU Dresden. Also the work with the finished chip is a collaborative project: "We produced 50 pieces of Tomahawk2 and 20 of them were packaged. So a few groups can use the chip, for instance scientists at TUD's Computer Science Department. They build an operating system for the chip or run database queries on it." For the next chip generation, collaboration with other groups is planned as well. The engineers are targeting GFDM (Generalized Frequency Division Multiplexing) applications which will be the coming technology of signal processing in the 5G standard. In the mid-term, also the construction of a chip with carbon nanotubes is envisioned which will be possible only through heavy cooperation with cfaed's Carbon Research Path.



Tomahawk2

Collaborators:
Uwe Aßmann, Jerónimo Castrillón, Gerhard Fettweis, Jochen Fröhlich, Hermann Härtig, Wolfgang Lehner, Christian Mayr, Wolfgang Nagel, René Schüffny, Marcus Völp, et al.

Institutions:
cfaed; TU Dresden; ZMDI (now IDT)

Path: Orchestration

DOIs:
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10.1145/2517087

CompSc EE

SREX: Secure Remote Execution

The SREX idea focused on the investigation of safe and secure execution of programs on a possibly untrusted hardware. This topic quickly gained in popularity due to several recent trends: First, modern computers are built from smaller and cheaper components, which are known to provide worse reliability. Therefore, an era of inherent unreliability approaches, where hardware faults threaten the safe execution of programs. Second, the explosive growth of Internet results in a flood of information that can only be stored in the cloud, i.e., on a fleet of computers that can be accessed remotely. Since the computers in the cloud are managed by external IT companies such as Amazon or Microsoft, the user can never be sure that the cloud data is secure. Together, these two trends plead to develop an infrastructure to guarantee both safety and security. The SREX project aimed at developing generic dependable approaches oblivious to the underlying hardware. For example, safe and secure extensions of the implemented control- and data-flow checkers can be implemented on top of any (possibly unreliable) hardware architecture. As a result, approaches developed in the context of SREX can be applied to the emerging hardware composed of inherently unreliable materials and circuits.

Safe and secure extensions

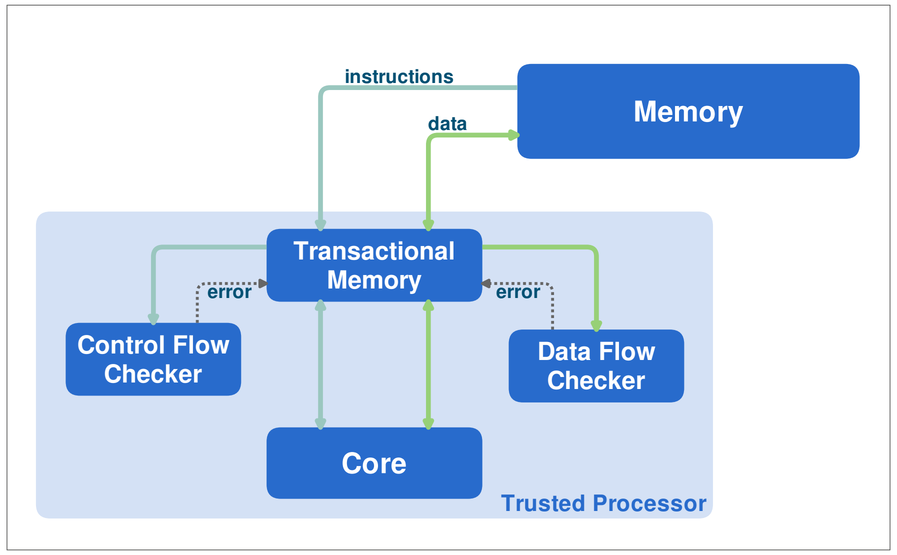
Cloud providers are primary targets for hacker attacks which can result in leaks of confidential information or deliberate incorrect execution of programs. Moreover, even if the cloud is protected against such malicious attacks, there is always a tangible chance that a random hardware glitch could corrupt the data. At the scope of more than 10.000 computers in modern clouds, such hardware faults become the norm rather than the exception. This two-fold challenge – security against hacker attacks in the cloud and safety against hardware faults – motivated the SREX team. SREX encompasses a range of sub-projects, starting from theoretical attempts to estimate the feasibility of malicious attacks and ending with concrete hardware designs to cope with hardware glitches. One of the several SREX sub-projects focused on the 'safe and secure' extensions to the state-of-the-art hardware. The final goal was to provide an infrastructure for safe and secure execution of arbitrary programs on next-generation computers.

Design

From a high-level view, both hardware faults and malicious attacks lead to a deviation of the correct 'path' of the program's execution. Therefore, to detect these faults and attacks, it is enough to check periodically that the program still follows the correct 'path', and if not, the program must be roll-backed, i.e., put back on the correct path of execution. Unfortunately, if a program executes on some cloud computer, one does not have any direct control over what and how executes on this computer. But, with some help from the hardware, it can be ensured that the program follows a correct path. The intuition here is that faults and attacks cannot bypass the protection given by hardware extensions. Put simply, some minimal changes to the existing computers' hardware can detect the execution of incorrect paths and roll-back programs to continue correct execution. The SREX group developed a set of such hardware extensions (see Figure). This set consists of three independent and mutually complementary components: (I) a Control Flow Checker that ensures correct control path, (II) a Data Flow Checker that ensures correct data operations, and (III) a Transactional Memory that performs roll-backs in case if one of the checkers notices an error (hardware fault or hacker attack). These hardware extensions can be embedded into existing computers and can protect arbitrary programs.

Progress and future plans

The Control and Data Flow Checkers are implemented and described in the corresponding papers in two prestigious conferences: SRDS'2015 and DSN'2015 respectively. The paper on a Data Flow Checker (named "Δ-encoding") received a Best Student Paper award. The third component – Transactional Memory – is also implemented and the paper submission is in progress. Plans include combining the three components into one complete system and performing extensive evaluation of the approach.



Hardware extensions for security and safety of applications. Control Flow and Data Flow Checker perform integrity checks of running programs and inform Transactional Memory to roll-back in case of detected errors

Speaker: Prof. Christof Fetzer

Sergei Arnautov, Christel Baier, Rasha Faqeh, Gerhard Fettweis, Martin Hahmann, Hermann Härtig, Carsten Janda, Eduard Jorswieck, Till Kolditz, Dmitry Kuvayskiy, Wolfgang Lehner, Linda Leuschner, David Öhmann, Benjamin Schlegel, Tobias Stumpf

Institutions:
cfaed; TU Dresden

Path: Resilience

CompSc EE

Delta-Encoding: Practical Encoded Processing

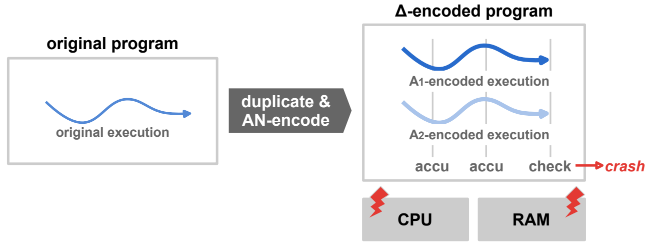
New materials and emerging distributed designs lead to increasingly interconnected and unreliable hardware which dictates the need for safety measures implemented on the architecture and software level. In addition, the upcoming Internet of Things implies that all computing devices will be connected to Internet at all times. Such connectivity poses a threat of remote hacker attacks. These two challenges require new approaches to improve both safety and security of modern software systems.

Status quo

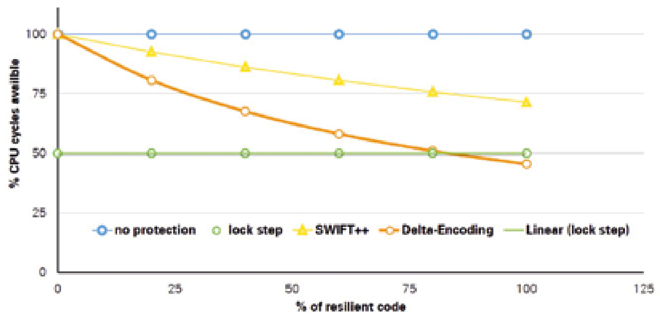
Prof. Christof Fetzer and his PhD student Dmitrii Kuvaiskii propose a series of approaches to improve both safety and security of software systems. The novelty of the proposed approaches is in the high coverage with respect to both hardware faults and malicious attacks. Safety is an ability of a system to detect and possibly tolerate (recover from) random unexpected faults or 'glitches' occurring in the underlying hardware. Safety is an important requirement for all embedded and especially safety-critical systems, e.g., in the automotive domain, airspace, or medical devices. In safe systems, the designer first analyses the classes of faults that can occur with high probability, building a so-called 'failure model'. Next, based on the failure model and assumed fault rates, an appropriate safety measure is chosen to protect the overall system. Security implies protecting the system against faults caused by the incorrect behavior of the system itself. So-called 'security holes' occur because programmers often make subtle mistakes when writing programs. These mistakes can go undetected during the testing process, such that they emerge in production. These software bugs can be used by the malicious attacker to take control over the whole system and cause severe damage. Security measures thus try to detect these bugs proactively. "Recently we noticed lots of unauthorized system intrusions. A significant part of today's infrastructure is controlled via internet, so our systems are critically vulnerable to intrusion," Fetzer describes the situation. Thus, the goal of the Resilience Path is to provide new methods for transparent safety and security of already-existing systems.

Methods

Traditionally for safety, two different CPUs (Central Processing Units) that run the same program and compare their execution results (signatures) were used – so-called 'lock-step computing'. Due to increased Internet connectivity, these CPUs are exposed to remote attacks, and hackers can intrude into the system and manipulate both copies of the program. The approach proposed by the Resilience Path can cope with such scenarios.



The idea of Delta-encoding is to replicate the data flow of a program. Each flow is encoded with a different code such that decoding of variables is very fast.



Delta Encoding requires less CPU cycles than lock-step CPUs as long as not all code needs to be protected. Delta-encoding also detects systematic failures – which are not detected by lock-step CPUs.

Adding the cryptographic extension

To make sure that execution signatures are not faked by the attacker, Fetzer suggests to use cryptographic extensions to achieve security guarantees. Only entities who know the private key can define the sequence of correct signatures. Of course, there are mechanisms to protect the key itself. Furthermore, the software system will be extended to one more mechanism called 'Guardian' that has the sole task of checking incoming execution signatures. If the 'Guardian' detects an unexpected flow of signatures, it detects the ongoing attack and stops the whole system execution to prevent any data corruptions or leaks. Preliminary results indicate that applications hardened using the proposed technique have less than two times performance overhead and fault coverage of 99.9 % (assuming no control flow faults). To sum up, the aim of the approach is to take care of security holes by protecting the execution of the programs to make sure that all the data is processed according to the specification and cannot be manipulated in a malicious way.

Outlook

The proposed approaches are currently tested and can detect and tolerate most of the occurring errors. For example, the proposed Delta-encoding copes with hardware faults and achieves very high fault coverage at the same time exhibiting moderate performance overheads. The patent process for Delta-encoding, the Guardian and the execution signatures has already started and there are already some projects with local companies to build hardware extensions. The Resilience Path also aims to push the proposed approaches to cloud systems.

Collaborators:
Christoph Fetzer, Dmitrii Kuvaiskii

Institutions:
cfaed; TU Dresden

Path: Resilience

DOI: 10.1109/SRDS.2014.62

CompSc

Resilient Software Systems

Parallel and distributed systems are a pervasive component of the modern computing environment. Clusters of multicore nodes have become ubiquitous, powering not only some of the most popular consumer applications such as web search and social networks but also a growing number of scientific and enterprise workloads. Dr. Pramod Bhatotia's prior research projects centered around building incremental parallel and distributed systems that enable existing real-world applications to transparently and efficiently benefit from incremental computation. His approach requires neither departure from current models of programming, nor the invention and implementation of application-specific dynamic algorithms for incremental computation.

Data analytics systems for stream processing

As individual users become increasingly concerned about their privacy, the desire to keep personal data on users' own devices yet still allowing analysts to perform real-time data analytics presents an interesting three-way tradeoff between privacy, utility, and latency. Users seek strong privacy guarantees, while analysts strive for high-utility data analytics with low latency, i.e., stream analytics.

Bhatotia's group works on designing and implementing StreamX, a practical system that provides privacy-preserving stream analytics without strong trust assumptions. StreamX scales well, requires no synchronization, and puts minimal trust on system components.

Incremental approximate computing

Approximate computing is used for speeding up computations, and efficiently utilizing the computing resources. The idea behind it is to return an approximate answer instead of the exact one. The trick is to choose a representative sample of the input data for computing instead of computing over the entire date. It allows users to trade-off query accuracy for the response time, enabling interactive queries over massive data by running queries on data samples and presenting results annotated with meaningful error bars.

Incremental computation tries to achieve the same goals as approximate computing; i.e., speeding up jobs and efficient resource utilization. However, incremental computation relies on reusing results across jobs instead of re-computing over the entire data from scratch. The idea behind incremental computation is to memoize the intermediate results of sub-computations, and reuse the intermediate results for the sub-computations that are unaffected by the changed input. Bhatotia's group built a data analytics system that combines the benefits of approximate and incremental computing. The idea is to design a sampling algorithm that would bias the sample selection in such a way that will give more weight to the input records for which they already have memoized results. The paper on this work was accepted at the 25th International World Wide Web conference.

Dependable systems leveraging new ISA extensions

Data provenance strives for explaining how the computation was performed, by recording and presenting a 'trace' of the execution to the user. The provenance trace is useful to debug multithreaded programs. To support provenance for unmodified executables, Bhatotia builds a POSIX-compliant data provenance library for shared-memory multithreaded programs. The data provenance library would be completely transparent and easy to use: it can be used as a replacement for the threads library by a simple exchange of libraries linked, without even recompiling the application code.

Data provenance for multi-threaded programs

To achieve this result, the group has designed the library to operate at the compiled binary code level by leveraging Intel PT ISA extensions. More precisely, they leverage the operating system-specific mechanisms to derive the data-flow and thread schedule, and make use of Intel Processor Trace (PT) feature to derive the control flow. Then they are able to combine the data-flow, control-flow, and thread schedule information to build a provenance graph for multithreaded execution, and thereby, aiding the developers to debug multi-threaded programs.

Hard-assisted fault tolerance

The current trend for smaller transistor sizes and lower operating voltages leads to hardware becoming less reliable. The errors can propagate to the software level and lead to unexpected program crashes and silent data corruptions (SDCs). There are anecdotal evidences when transient faults in hardware led to random data corruptions as in Google or even unplanned outages as in case of Amazon S3. To address this problem, Bhatotia's group built a compiler framework based on Hardware-Assisted Fault Tolerance (HAFT) for multithreaded programs. Their compiler framework detects faults in computation utilizing Instruction-Level Replication (ILR), and employs Hardware Transactional Memory (HTM) to recover from these faults. This paper on this work was accepted at ACM EuroSys 2016.

Triple modular redundancy

Instruction-Level Redundancy (ILR) is one of the well-known approaches to tolerate transient CPU faults. In this work, it was noticed that the core idea of ILR is to execute the same action on several copies of data, which is exactly the definition of Single Instruction Multiple Data (SIMD) technique. Thus, the hypothesis is that the triplication of an instruction in ILR can be replaced by a single SIMD instruction on three copies of data to achieve lower performance overheads. To verify this hypothesis, Bhatotia designed and implemented ELZAR, a compiler framework to provide triple modular redundancy utilizing Intel AVX, new ISA extensions for vectorization. ELZAR transforms unmodified multithreaded applications to transparently detect and correct transient faults.

Collaborators:
Pramod Bhatotia, Rasha Faqeh, Pascal Felber, Christof Fetzer, Dhanya R. Krishnan, Dmitrii Kuvaiskii, Do Le Quoc, Rodrigo M. Rodrigues

Institutions:
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Path: Resilience

DOIs:
10.1145/2901318.2901339
10.1145/2872427.2883026

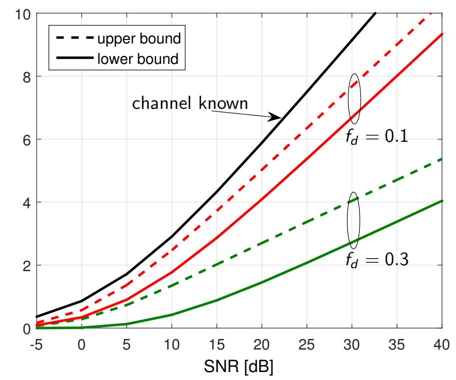
CompSc

Maximum Rate of Reliable Communication on Mobile Radio Channels

Dr.-Ing. Meik Dörpinghaus' research has been always guided by his deep interest in understanding the principles and limits of reliable communication. While for the basic model of an additive white Gaussian noise channel Claude Shannon provided a remarkable elegant answer to this question in his landmark paper "A Mathematical Theory of Communication", for more practical channel models describing modern mobile communication systems the answer on the maximum achievable rate of reliable data transmission is still an open question. Dörpinghaus' work led to some fundamental contributions in this area by questioning standard modeling assumptions made in prior work which yield to way too pessimistic results on the achievable data rate.

A moving cell phone observes a wireless channel with permanently changing quality and characteristics. Effectively, the input signal is multiplied by some random quantity and then some additive noise is added. The multiplicative factor is temporarily correlated depending on the speed of movement of the cell phone, e.g., it is less correlated when moving in a fast train in comparison to a walking pedestrian. The dynamic of these changes of the channel has a direct impact on the channel capacity, i.e., the maximum rate of reliable communication. In recent years, there has been a lot of effort to characterize this capacity.

Prior work provides bounds on the capacity clearly showing that the achievable data rate heavily decreases with increasing channel dynamics due to the lack of knowledge of the channel characteristics at the receiver (see figure).



Bounds on the achievable data rate with symbol rate sampling and Gaussian input symbols showing the degradation due to the lack of channel knowledge depending on the maximum Doppler frequency f_d

Especially, the slope of the capacity in the high signal-to-noise ratio regime strongly decreases with an increasing maximum Doppler frequency, i.e., an increasing channel dynamic.

Choosing the right model

Prior work is based on a very standard symbol rate sampling channel model. This means that the received signal is sampled at a rate corresponding to the bandwidth of the channel input signal. However, the multiplicative disturbance of the channel input signal due to the changing channel leads to a bandwidth expansion. Thus, following Nyquist theorem the channel output signal has to be sampled at a higher rate than the symbol rate to be able to retrieve all the information it carries on the channel input signal. The usually discussed symbol rate sampling is not able to provide a sufficient statistics of the input signal, i.e., the samples do not contain all available information. Hence, this model does not sufficiently reflect the behavior of the actual underlying continuous-time channel. This finding was Dörpinghaus' motivation to study the capacity of the actual continuous-time channel.

Approach and result

The study of the capacity of the underlying continuous-time fading channel is a mathematically very challenging problem. Thus, as an initial step Dörpinghaus studied the behavior of the slope of the capacity over the signal-to-noise ratio (SNR) in the high SNR regime, which is typically referred to as capacity pre-log factor. For symbol rate sampling the pre-log factor linearly decreases with the maximum Doppler frequency. Differently, together with collaborators from different leading European universities Dörpinghaus was able to show that by sampling the channel output signal at twice the symbol rate, i.e., by doubling the sampling rate with respect to the symbol rate model, this pre-log degradation completely disappears. By such an oversampling the pre-log factor becomes independent of the channel dynamic and equal to the case when the channel is known by the receiver (see figure).

In conclusion, this result shows that the capacity of the continuous-time fading channel is significantly larger than the capacity of the symbol rate sampling model. On the one hand, this provides a striking example for showing the importance of careful modeling. On the other hand, it shows that significant increases in performance might be achievable by using such oversampling techniques in practical systems. A first paper on this topic was accepted quickly for publication in 'IEEE Transactions on Information Theory'.

Collaborators:
Meik Dörpinghaus, Giuseppe Durisi, Günther Koliander, Heinrich Meyr, Erwin Riegler

Institutions:
cfaed; RWTH Aachen University; Chalmers University of Technology; ETH Zurich; Vienna University of Technology

Path: HAEC

DOI: 10.1109/TIT.2014.2339820

Phys Maths CompSc EE

HAEC
Highly Adaptive Energy-Efficient Computing

In 2012, information and communication technology already accounted for almost 5 % of the worldwide electricity consumption with annual growth rates of 7 % corresponding to a doubling per decade. To break this trend, it is important to enable highly energy-efficient computing infrastructures without compromising performance. This goal directly reflects the research vision addressed by the DFG Collaborative Research Center 912 HAEC (Highly Adaptive Energy-Efficient Computing). To turn this vision into reality, HAEC addresses key research questions concerning hardware, software as well as system challenges by creating innovative leading edge technology for novel computing architectures and energy-adaptive distributed hardware and software.

Goals and visions
HAEC aims at a holistic approach of energy adaptivity, taking into account energy efficiency at all levels as a joint optimization problem, ranging from the transistors, over the communication architecture up to the software engineering with an energy-aware computing management. In the long term, HAEC strives to implement the vision of a HAEC Box, a highly performant but energy-adaptive computing platform with an overall volume of just one liter hosting a billion of individual cores with TBytes of main memory. By utilizing novel chip integrated optical and flexible wireless chip-to-chip communication technology developed within HAEC, the HAEC Box will allow a new level of run-time adaptivity of future computers. This enables a platform that flexibly adapts to the needs of different algorithmic problems. Multiple control loops at design- and run-time will be researched, which shall be controlling the energy trade-off based on the current hardware state as well as the application requirement in terms of performance.

Key results and innovations of Phase I
Phase I of HAEC brought many pioneering innovations, both project specific as well as those being central for the CRC. A few examples are: the design of adaptive wireless and optical communication components, new communication approaches using oversampled 1-bit analog-to-digital conversion, beam-switching based on Butler-matrices, energy measurement test systems, the energy-efficiency analysis of fundamental network elements, a hierarchical framework of energy-utility functions, a system-wide knowledge plane and many more.
Apart from the scientific achievements of the individual project groups, experience on the day-to-day work and, moreover, the increase of the number of projects in Phase II (2015-2019), led to a reorganization of the CRC into now three project groups:

I. Energy-adaptive high-speed communication platform (HAEC-Hardware)
II. Energy-adaptive computing and network architecture (HAEC-Architecture)
III. Energy-adaptive computing management (HAEC-Software)

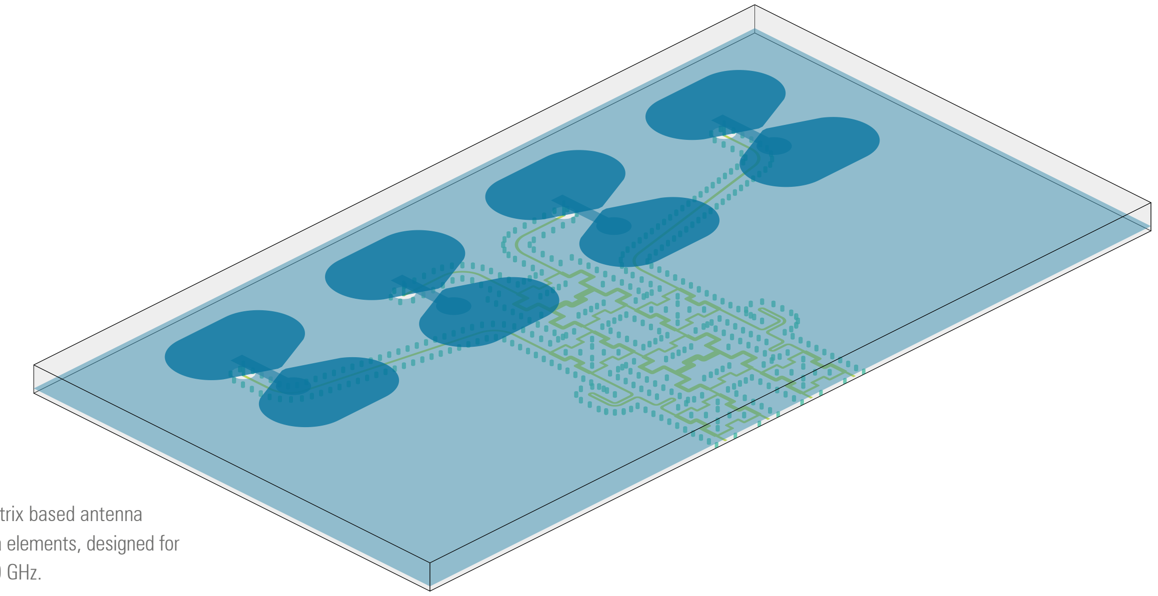
Goals for Phase II and outlook
While in Phase I concepts and first demonstrators for the communication architecture have been developed, several further problems have to be tackled to enable the new communication platform for the HAEC Box. Concerning the optical links, in Phase II the data rate will be increased to 100 Gbit/s (from 25Gbit/s) by using techniques like analog predistortion and wavelength division multiplexing. Regarding the 100 Gbit/s wireless links the components developed in Phase I will be further enhanced and merged. Also, the overall integration of the wireless and optical components into the chip-stack is one goal for Phase II. On the software side, Phase I enabled the instantiation of various energy control loops and the performance of energy-optimizations "in the small". Phase II aims at tightly integrating the individual energy-optimization techniques to enable system-wide global adaptivity. Since the final architecture of the HAEC Box allows placing millions of cores into a single system, NUMA-awareness needs to be considered as a major design requirement. Finally, the programmability of the HAEC Box will be improved by developing high-level languages especially for data-intensive applications. Finally, in Phase II a first joint HAEC Box demonstrator called HAEC Playground will be built merging the results of all projects. This demonstrator provides a mean for testing developed mechanisms in a holistic manner. The overall goal is to illustrate the superiority of the HAEC Box in a smaller scale. In that vision, the HAEC Box architecture needs to be defined, including modelling its components and integrating applications and component models.

Integration into cfaed
With energy-efficiency, HAEC addresses a major cfaed challenge and its efficiency techniques have the potential to be integrated in the novel hardware/software architecture. On the one hand, new technologies from the BAC and Carbon Paths could allow for breakthroughs for developing the new interconnects within the HAEC hardware area. On the other hand, techniques addressing energy utility and resilience mechanisms researched in the Orchestration and Resilience Paths can be applied in the HAEC box.

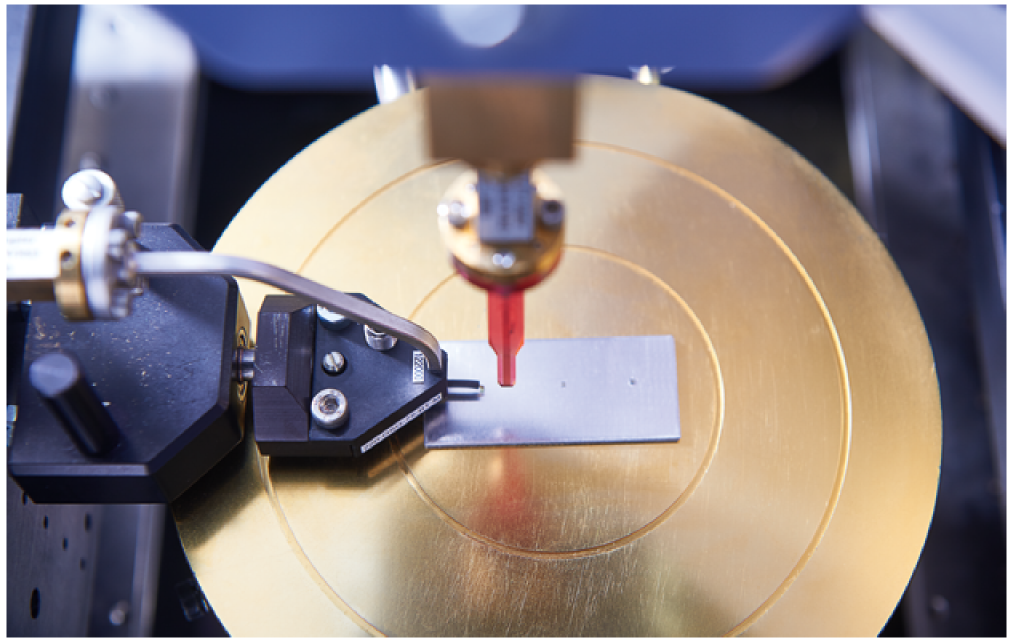
Speaker:
Gerhard Fettweis

Vice-Speakers:
Christel Baier, Wolfgang Lehner, Wolfgang Nagel, Dirk Plettemeier

CompSc EE



Design of a 1x4 Butler Matrix based antenna array with bow-tie antenna elements, designed for operation from 170 to 200 GHz.



Advanced near-field antenna measurement setup for on-chip antenna characterization at microwave frequencies

HAEC Playground

Delay-Induced Self-Organized Synchronization in Electronic Networks

In modern electronics miniaturization often leads to a higher sensitivity of the individual electronic components which makes them more vulnerable to the effects of noise and fluctuations. Alexandros Pollakis and Lucas Wetzel investigate new concepts for electronic networks that ensure reliable operations in noisy environments. Biological systems have evolved to deal with exactly these challenges – miniaturized components in noisy environments that work robustly. Their research focuses on synchronization which can be simply described as the coordination of clocks. The idea was to learn how synchronization problems are solved in biological systems and to apply these principles in electronic systems. It is known that biological systems work reliably in highly noisy environments – how would this play out in electronics? The group of scientists found striking similarities between the model descriptions in these different 'worlds'.

Synchronization

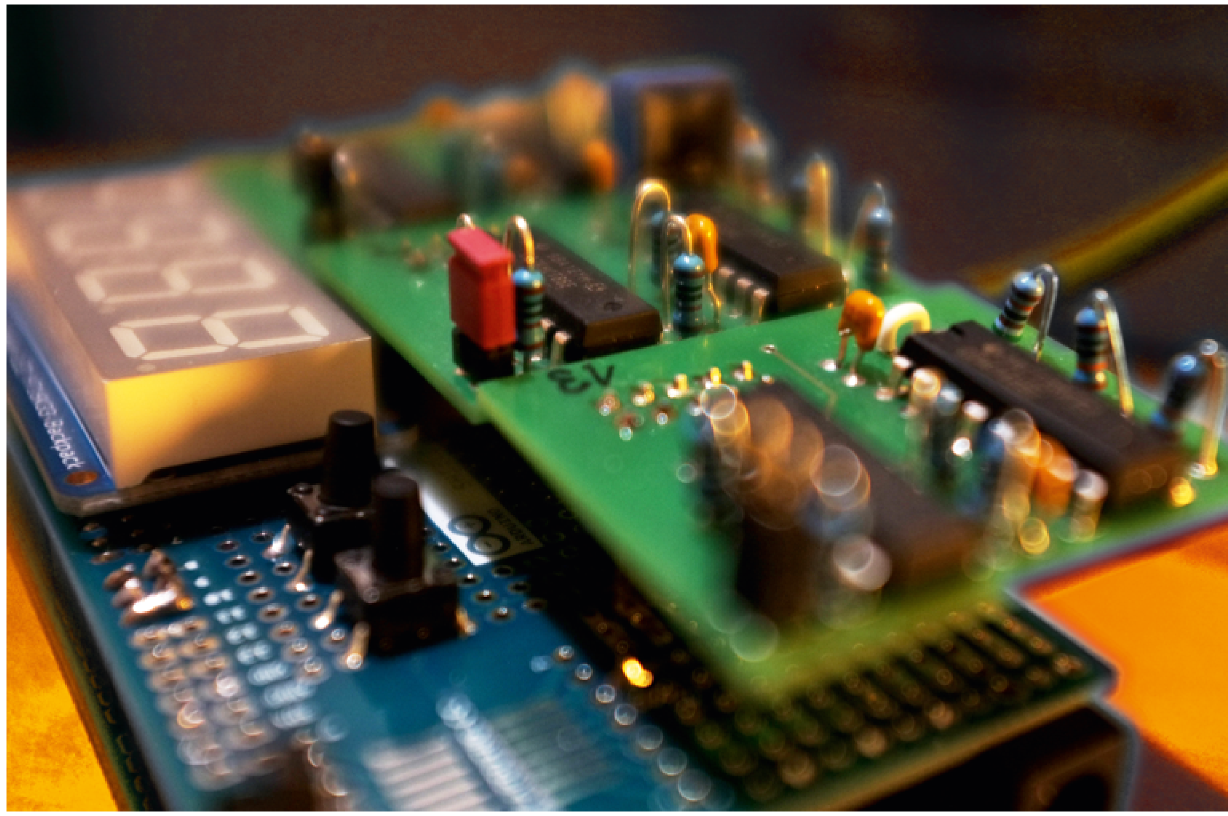
Synchronization is of fundamental importance for many technical applications, e.g., the global positioning system (GPS). There are different kinds of synchronization: Frequency synchronization means two clocks running at the same speed, but not necessarily showing the same time. The case that the clocks show the same time and run at the same speed is usually called in-phase synchronization. Current solutions to provide synchronicity reach their limits in many respects, for example when the oscillators or clocks are spatially distributed. Due to finite signal transmission speeds, such systems are subject to communication delays that can have a tremendous effect on the stability or functionality of the system.

Learning from biological systems

Most common in technical applications is the master-slave-approach to synchronize clocks: one master clock communicates the time signal to one or many slave clocks. "In contrast to that, we propose a biological inspired approach which is fundamentally different. The basic principle in biological systems is that a multitude of biological oscillators is mutually connected via specific bio-chemical signaling pathways and self-organizes a common rhythm through the interaction of the individual oscillators", describes Pollakis. A famous example is the Circadian Clock in the human hypothalamus, which is entrained by the daylight cycle. To bring together biology and electronic engineering, a cooperation of TUD's Vodafone Chair Mobile Communications Systems and the Max Planck Institute for the Physics of Complex Systems was established. Pollakis and Wetzel investigate networks of coupled electronic clocks, implemented with Phase-locked Loops (PLL), in the absence of an entraining master clock. The goal of this project is to identify optimal synchronization strategies, including coupling architectures and boot strategies that allow efficient and robust synchronization in different settings. Such systems self-organize synchronized states and continuously counteract imperfections in synchrony by constantly reducing perturbations, e.g., induced by internal and external noise. "In our approach the clocks exchange signals with other clocks in the network. Setups like this were proposed before, but our contribution is that we established a theoretical model description that enables us to study, analyze, and understand synchronization phenomena in the presence of communication delays and signal filtering," describes Wetzel.

Multi-stability and phase model

Communication delays in such mutually coupled systems can lead to multi-stability: for a given setup there can be different stable states that the system can attain depending on how it is started. The frequencies of the coupled system deviate from the frequencies of the individual components – the whole system speeds up as components always 'see' their neighbor ahead of them, or slows down, because the coupling partners are seemingly lacking behind. "We derived a phase model, an abstract description that considers the current state of oscillation within one cycle. We can apply it universally to various scenarios. The model allows us to study the impact of the different components playing a role in such settings. It allows us to analyze analog and digital signals, and different coupling functions which are determined by the type of phase detectors that are used. We have built prototype networks to compare the theoretical predictions with the results obtained from experimental measurements and found that they were in good agreement," Pollakis sums up. "The project has discovered interesting new results for networks of mutually coupled electronic oscillators. We have shown how



Demonstration setup with 3 coupled digital PLLs and a microcontroller that sets the coupling and transmission delay

two factors that individually hinder synchronization in such systems will together enable robust synchronized states."

Future plans

Pollakis describes one big advantage of this technology: "If you have low-quality oscillators and you couple them according to our concept, you can achieve a much higher quality." The scientists explore the applicability for high performance Multiprocessor System-on-Chips (MPSoCs) and Multiple Input Multiple Output (MIMO) wireless communication architectures, distributed antenna arrays, and other large scale electronic clocking systems communicating by means of time-continuous signals. Communication technologies like LTE or 5G could benefit greatly from antenna arrays comprising 100s or 1000s of synchronized antennas. Also power grids or computer networks may profit from systems of mutually coupled PLLs. However, a lot remains to be done, and the group now aims for a better understanding of the influence of noise, and to quantify how much more robust their alternative concept really is. The basis for further research on this topic is finding new partners in academia and/or industry.

Networked research

This achievement is a result of a collaboration between Vodafone Chair and the MPI-PKS. Wetzel confirms: "This collaboration initiated by the cfaed combined the experience of engineering, physics, and biology very well and it advanced quickly. We have been working for two years and can now look back on really promising results, three published papers and a patent application which is underway. I think, this was quite effective!"

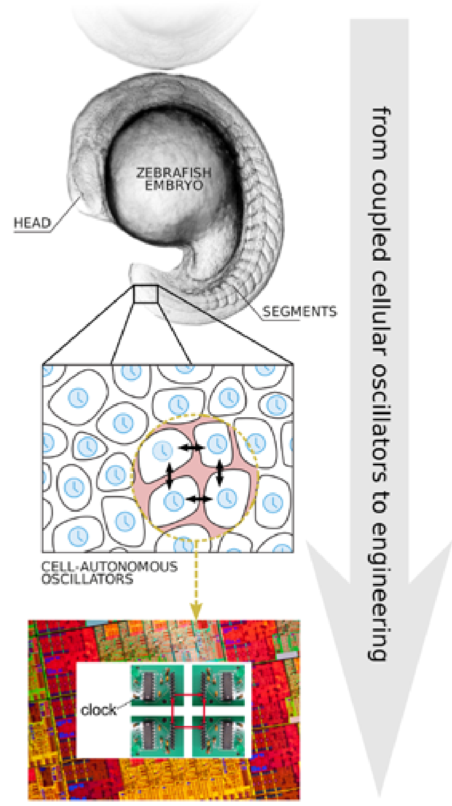
Collaborators:
Gerhard Fettweis, David J. Jörg, Frank Jülicher, Alexandros Pollakis, Wolfgang Rave, Lucas Wetzel, et al.

Institutions:
cfaed; MPI PKS; TU Dresden

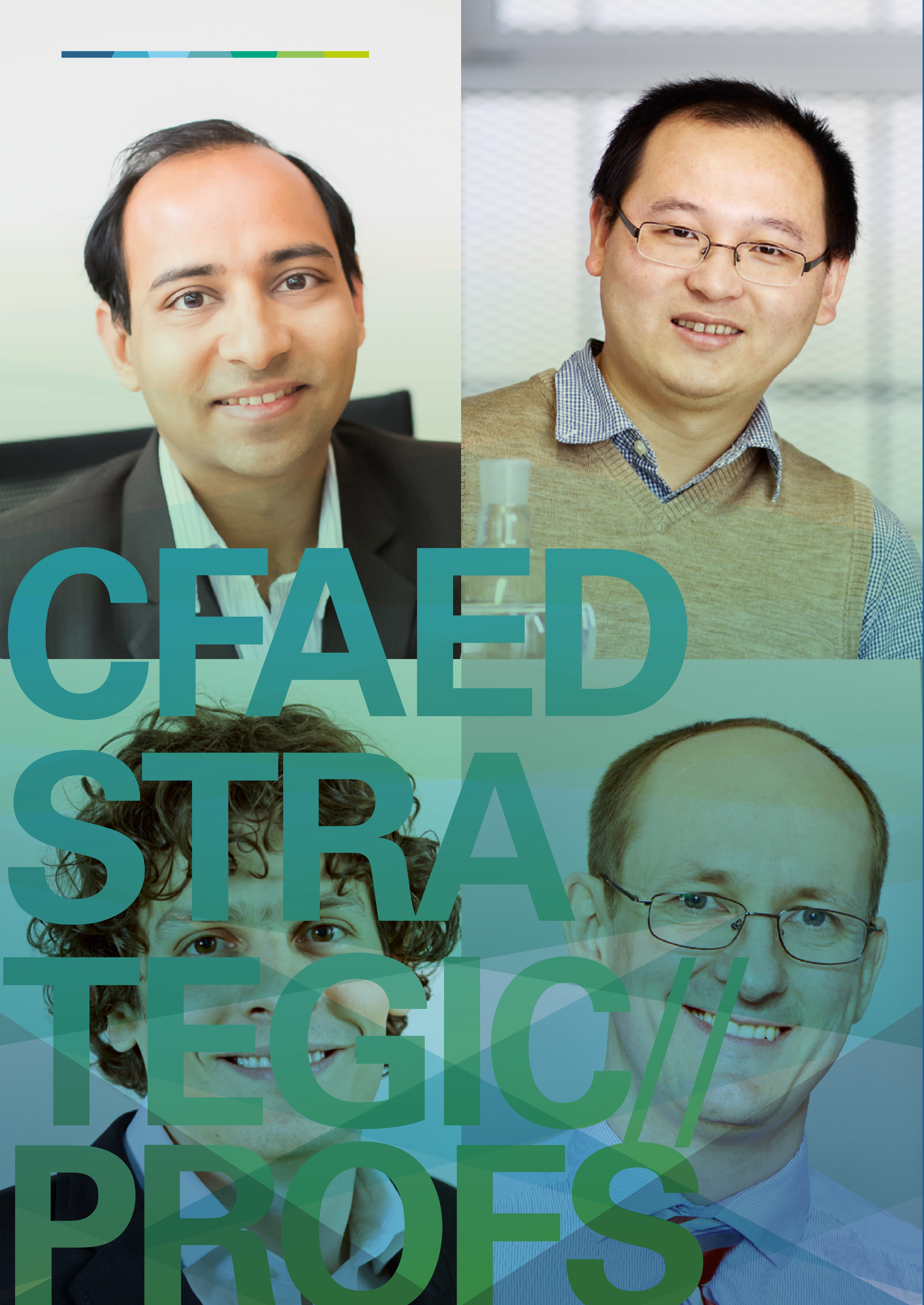
Path: Biological Systems

DOIs:
10.1088/1367-2630/16/11/113009
10.1109/ICC.2015.7248572

Bio Chem Phys CompSc EE



Cellular clocks synchronize locally due to mutual biochemical interactions to coordinate vertebrate segmentation - this concept can be transferred to networks of electronic clocks.



"The important thing is to not stop questioning. Curiosity has its own reason for existence."
Albert Einstein

JERÓNIMO CASTRILLÓN
cfaed Chair for Compiler Construction

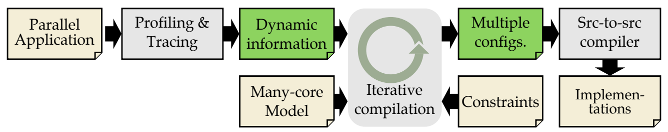
What did you want to be when you were growing up?
A scientist
What is top of your bucket list?
A hot air balloon ride over Africa
What fascinates you most about your job?
Meeting new people who impress me greatly – for example Gene Myers at the output.dd event of the Computer Science faculty in 2014
What place feels like home for you?
Colombia
What do only few people know about you?
I like to dance Salsa.

Research
"The call for the professorship appealed to me as it listed most of the research topics that I work on or that interest me". Only one year after completing his PhD at RWTH Aachen, Professor Jerónimo Castrillón received the call from TU Dresden for a cfaed Strategic Professorship. The Chair's mission is to improve the efficiency – in terms of performance, energy consumption, and/or productivity – of programming heterogeneous computing platforms for domain-specific applications. Research at the Chair focuses on: (I) parallel programming of heterogeneous platforms (studying algorithms for deploying parallel programs, e.g., dataflow programming models, onto heterogeneous platforms while taking data placement and energy consumption into account), (II) domain specific languages (DSLs) and tools (parallel languages based on traditional programming paradigms, e.g., C programming) limit the applicability of algorithmic-level optimizations, and investigating DSLs for specific application areas (e.g., computational biology), (III) tools and methodologies for post-silicon technologies (investigating new challenges posed by emerging technologies for future programming tools), and (IV) optimization techniques (a horizontal research line that seeks to investigate optimization techniques that can deal with the complexity of the optimization problems associated with high level code transformations and generation).
The international team of researchers approach their work in an interdisciplinary way and work with other groups, for example with computational biologists at the Max Planck Institute of Molecular Cell Biology and Genetics.

Plans and visions
"I strive for high quality and innovative research results and, of course, international recognition of our results. However, I would like to just do my research without thinking too much about the common evaluation standards but it is quite difficult not to follow the rules." As a Professor, Castrillón is also responsible for his Chair's members and he wants to offer ideal research conditions as well as a good working atmosphere. As a teacher, Castrillón enjoys engaging with young scientists and supports the Cluster's structured program to foster the careers of young academics.

Transfer
Even though the research is very fundamental, its focus is also on applications. As the leader of the Orchestration Path of cfaed, Castrillón uses the Tomahawk Chip developed by Prof. Fettweis' Vodafone Chair Mobile Communications Systems, to drive the fundamental research of this path. This means, that the application determines to a certain extend which issues must be investigated in order to make it more efficient, fault-tolerant etc. Castrillón is also an investigator of the Collaborative Research Center HAEC and leads the project 'Languages and Compilers for Energy-Efficient Programming'. He has a close cooperation with Silexica Software Solutions. Silexica is an award-winning company that provides tools for programming embedded multicore architectures. Together with the Silexica team, he works on the extraction of parallelism from C code and mapping of process networks to multicores.

Societal Impact
ICT is a powerful driver for many aspects of today's society, such as quality of life and science. Reducing the technical complexity, positively influences the speed of scientific advances. On the other hand, electronic data processing becomes more and more expensive. Therefore, it is paramount to increase the efficiency continuously in order to reduce the negative impact. Castrillón and his group aim at contributing to support this ambition in their daily work.



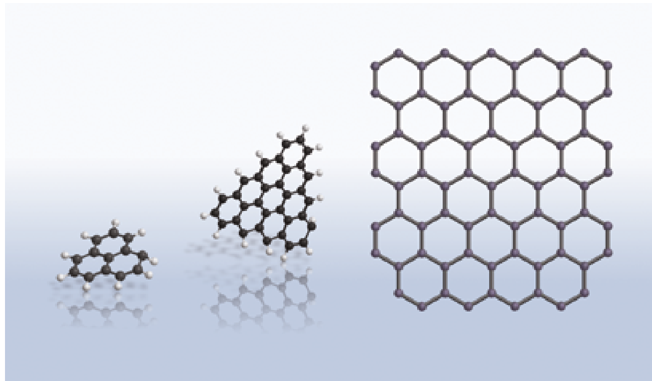
Sample programming flow, where execution traces are analyzed in an iterative optimizing compiler. The compiler uses an abstract model of the target multi-core and generates multiple possible mappings that meet application constraints. Implementations can be then switched at runtime.

Path: Orchestration

XINLIANG FENG
cfaed Chair for Molecular Functional Materials

What would your super power be?
To be able to work much harder without breaks
What is your favorite App?
Google Maps
What fascinates you most about your job?
Discovering new molecules or materials
What place feels like home for you?
Dresden
What do only few people know about you?
I enjoy playing basketball.
What was your most important research achievement?
Graphene nanoribbons, which I worked on in collaboration with Prof. Müllen at MPI for Polymer Research in Mainz.

Research
Professor Xinliang Feng is an internationally recognized researcher in the area of graphene, two-dimensional nanomaterials, organic conjugated materials, carbon-rich molecules, and materials for electronic and energy-related applications. Since August 2014, he leads the Chair for Molecular Functional Materials at TU Dresden as cfaed Strategic Professor. Feng was listed as Highly Cited Researcher in 2015 (published by Thomson Reuters) for both categories – chemistry and materials science. His research focuses on fundamental synthetic organic chemistry combined with macromolecular and supramolecular approaches for the fabrication of materials used predominantly for electronics and energy applications to fulfill current and future demands of our highly technology dependent society.



From molecules to 2D materials

Graphene – the new superconductor
A very classical field within organic chemistry is the one of polycyclic aromatic hydrocarbons and heteroaromatics, probably best associated with its 150 years of tradition in dyes and pigments and a fundament of the German chemical industry, which is brought to a whole new level since the discovery of graphene in 2004 by Geim and Novoselov (Nobel Prize in Physics 2010). Graphene is an infinite, two dimensional honeycomb lattice of carbon atoms and poses record mechanical properties and exceptional electronic properties. For example, it is the strongest and thermally best conducting material known to man, being the thinnest (one atom thick) at the same time. Also, it has very high charge carrier mobility, which is interesting for applications in electronics. For tuning its properties, e.g., to use graphene materials in transistors, one needs to control the structure and defects, introduced by heteroatoms, as well. Rather than extracting graphene as a single layer out of graphite, Feng's group uses chemistry approaches to construct graphene inspired carbon nanostructures out of defined small molecules. This 'bottom-up' approach allows to define the materials properties on a molecular or atomic level. One example is the fabrication of graphene nanoribbons by the polymerization of defined monomers followed by planarization into stripes of graphene with perfect control of the ribbon widths and edge structures. In collaboration with physicists, it is possible to investigate how the designed structures influence the electronic properties. Furthermore, it is possible to visualize the perfect structure of the graphene nanoribbons by scanning tunneling microscope or atomic force microscopy. Another case is the bottom-up fabrication of two-dimensional covalent or supramolecular polymers. These materials can be considered as synthetic 2D structures with atomically precise induced defects. Here, monomers are polymerized at interfaces for example of water and air to obtain square centimeter sized electrically conducting organic sheets. The scope of this approach is unlimited and desired properties of the resulting materials such as electronic features may be introduced by the careful choice of monomers.

Transfer
The transfer of Feng´s research into daily life applications is a strong focus and his motivation to go beyond existing technologies. Until now, methods for the production of high-quality graphene suitable for use in electronics were missing. The application-oriented methodology developed at Feng's labs overcomes this challenge. This has already attracted industry partners who showed an interest in adapting this technology into industrial scale production.

Path: Organic/Polymer

AKASH KUMAR
cfaed Chair for Processor Design

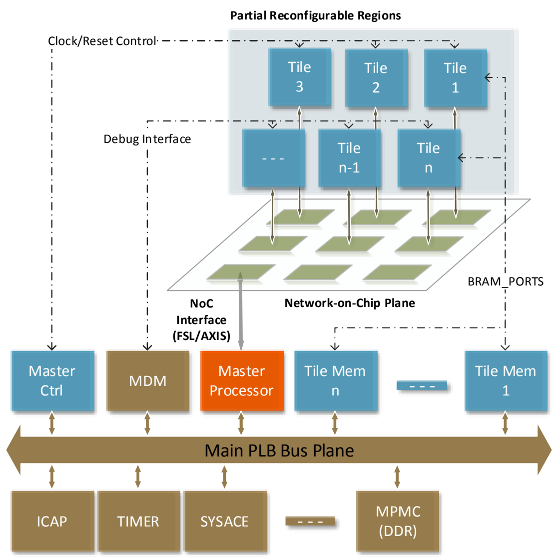
What did you want to be when you were growing up?
An astronaut
What makes a perfect day for you?
Long breakfast, sunshine, coffee, being with my family
What fascinates you most about your job?
Brainstorming with students
List three things only few people know about you.
I enjoy singing, playing the violin, and I like to cook.
Describe the most important research achievement/invention ever?
Mobile phones. My personal most important invention is probably a data encrypting memory stick which I developed together with students in Singapore.

Welcome to Dresden
Professor Akash Kumar joined cfaed in October 2015 and holds the Chair for Processor Design at TU Dresden's Computer Science faculty. Akash will be centrally integrated within the CRC912 – HAEC. His research concentrates on energy-efficient computing, high-performance architectures, novel lifetime models for such architectures, hardware verification, embedded design, designing resilient, fault-tolerant processor- and multi-processor systems, parallelization, and design of distributed computing architectures.

Research
Low power multiprocessor platforms are becoming faster and smaller and, at the same time, more fault prone. Therefore, research must focus around the development of fault-tolerant platforms that are able to avoid faults altogether (proactive) or that have a solution how to deal with faults if they occur (reactive). The proactive mapping or scheduling of a processor is based on software that determines which tasks will run on which specific processor. The reactive resource management must enable the move of the failing tasks to another processor within the platform. Akash's main focus will be on the power consumption and to find solutions about how to reduce the power and energy needed. In order to test his algorithms and architectures, he often uses Field Programmable Gate Arrays (FPGAs) to prototype them. He also designs novel algorithms for FPGA design-flow to make use of parallel computing architectures. One example of the low-power multi-processor architecture he developed is shown in the figure. The architecture is an example of a heterogeneous system where the idea is to match the hardware with the application as closely as possible, so as to keep the power consumption to a minimum. This architecture offers many advantages over existing works. First, thanks to the generic architecture of tiles, it is possible to relocate the partial bitstream to any compatible PR region. This technique reduces the design time and storage space significantly since one partial bitstream can be reused for many PR regions. Second, the task migration process and run-time loading of processor executable code can be done easily in the system because of the custom memory block wrapper called Tile Memory.

Teaching and working with students
"Brainstorming with students is one of my favorite parts of my job", Akash says. In that way, he developed a secure USB-KEY that plugs into a regular USB port on any computer and en-crypts/decrypts data on the fly, such that the data on the USB storage always remains encrypted and it requires a mobile app to authenticate the user. It also locks its content automatically after a certain idle period.

Outlook
The interdisciplinarity of cfaed, the local research and industry network opens up new collaborative chances for Akash within academia, non-university institutions, and industry. He has already approached local industry to transfer his research results into applications.



PR-HMPSoC (Partially Reconfigurable Heterogeneous Multiprocessor System-on-Chip)

Path: HAEC + Orchestration + Resilience

STEFAN MANNSFELD
cfaed Chair for Organic Devices

Which living person do you most admire, and why?
My mum. After having raised four kids, she re-started her professional career by selling flowers in front of a supermarket, then worked in a hospital, trained as a yoga teacher, learned to drive again and successfully startet a new career as an occupational therapist. She is my true heroine.
What is your favorite App?
'Follow Chess'
What is top of your bucket list?
To found and lead a cfaed choir
List three things few people know about you.
I am quite a decent basketball player. I am a huge fan of classical music. I enjoy drawing birthday cards.

Professor Stefan Mannsfeld's work is a mix of fundamental and application-oriented research. The current organic field-effect transistors (OFETs) are still too slow for growing demands and the challenge is that they can switch quicker between 0 and 1. The fundamental research investigates why and how certain materials behave in certain ways. The application-oriented part looks at possibilities to make use of the advantages in everyday life.

Organic materials
Transistors are one of the basic building blocks of microelectronics and they are traditionally built using silicon as it enables a very fast electrical transmission. However, owing to the high costs and energy footprint of producing silicon crystals and the inflexibility of the material, today's demand for inexpensive flexible applications cannot be met by using this conventional material. Therefore, the soft organic semiconductor materials are becoming ever more important in the production of transistors on curved, bendable or stretchable substrates. The aim is to shape and develop the markets of both organic materials and flexible circuit applications, building on the envisioned low cost of production for both.

Research
At Stanford University's SLAC (National Accelerator Laboratory), Mannsfeld participated in the advancement of printing transistors. For that, one must understand how each layer is formed and how it can be manipulated in such a way that each layer becomes electrically more efficient. Efficiency is highly important. The cooperation with Professor Ellinger (Chair for Circuit Design and Network Theory / Carbon Path) and Professor Voit (Chair for Organic Chemistry of Polymers / Organic/Polymer Path) is a particularly exciting challenge for Mannsfeld who leads cfaed's Organic/Polymer Research Path.
In cfaed, there are three research 'layers', namely (I) the production of innovative materials, (II) the materials science engineering of certain devices and (III) the integration into holistic systems. Ellinger's research focuses on how individual devices should be integrated into complex circuits while Voit designs high-performance materials for device applications. Mannsfeld's device research is thus bridging the gap between the raw materials and functioning electrical circuits. In order to accomplish their individual but also the global team goals, the cfaed scientists had to learn to speak the same language first. This can be a challenge since their fields of expertise are so different. Overcoming these challenges is, however, a very worthwhile goal since the collaborative research at cfaed allows the scientists to tackle unique and visionary goals.
Mannsfeld's latest achievement is a new highly conductive printed transparent electrode that enables better light harvesting or light emitting devices – this result was published in his paper 'Ultrahigh electrical conductivity in solution-sheared polymeric transparent films' in the Proceedings of the National Academy of Sciences USA, the second most cited journal across all fields of science in the US.

Transfer and potential applications
Potential applications for cost-efficient circuits based on organic materials are, for example, flexible displays. These can be used in many devices such as flexible smartphones that can be folded away and put in one's pocket, flexible labeling of freight that allows for more efficient goods logistics, or flexible lighting for very large or very small areas. Of course, applications in the field of medicine are the most pressing to be pursued as the conventional silicon is not biocompatible. Sensor technology, for example used in intelligent skin patches to measure temperature, pulse rate, and other important body functions, is only one potential use. Another important application would be a new generation of solar cells. Currently, silicon solar panels are very heavy. Organic solar cells can be thin adhesive foils and are produced already by the company Heliatek in Dresden. In summary, applications of organic, flexible electronics are lightweight and therefore portable, cheap, and as such, open up unprecedented possibilities in the electronics market.

A dedicated teacher
One of Mannsfeld's favorite aspects about his job is the teaching part. He enjoys teaching and to convey knowledge: "A 'Thank you, I finally got that now', is the best answer you can get from a student", he says.

Path: Organic/Polymer

"Logic will get you from a to z; imagination will get you everywhere."
Albert Einstein

PRAMOD BHATOTIA
cfaed Research Group Parallel and Distributed Systems

What would your super power be?
Actually, I'm happy with the things I have right now…
What did you want to be when you were growing up?
I wanted to be a cricket player! Cricket is the most common sports in India, I played it as a boy, but later I started liking computer science…
What is on top of your To-do-List?
At work: Writing a couple of grants.
In the personal area: I'd like to travel to South America, have never been there. One day I will take a long vacation and go there.

Research
Dr. Pramod Bhatotia's research focuses on computer systems; more precisely, any software used in modern computing, running on local machines, in the cloud, or in data centers. His interest ranges from distributed to operating systems. Overall goals are to make software robust against security flaws and software bugs, fault free, scalable, dependable, and basically secure. To achieve this, Bhatotia builds up a research group in cfaed's Resilience Path, which aims at making software systems dependable. Another field of interest lies in the evolution around the technology for the 5th generation network for mobile communications, in Dresden concentrated within the 5G Lab Germany.

First steps
"I'm really excited about the 5G Lab concept. Applications of the Tactile Internet require a very low-latency response. Since I have a background in building big systems for real-time processing of data, I am targeting some of the things that are being looked at in the 5G Lab." Bhatotia also started working on another field called approximate computing. It describes solutions where queries do not require absolute exact answers but merely approximate results. These can be provided much faster – a principle which can be found already today in most of the recommendation engines in the internet.

Personal note
Bhatotia joined cfaed in Spring 2015 after finishing his PhD thesis at the Max Planck Institute for Software Systems (MPI-SWS) in Saarbrucken. "I experienced the German lifestyle during that time and the opportunities of doing research in Europe, which are significantly driven by the strong governmental support for fundamental research." This experience convinced him to stay in Europe. "Dresden hosts one of the strongest groups in systems research in Germany. Also, the excellent research conducted within cfaed convinced me to come here," Bhatotia reflects his decision to come to Saxony.

Academia vs. industry
Bhatotia had worked in industry before he entered his career path in academia. In India, he was a member of technical staff at IBM research. He decided to pursue a scientific career and started his PhD at MPI-SWS. "Over the years I got more and more attracted by the advantages of the academic surroundings, e.g., enjoying scientific freedom and working with students. It is a satisfying feeling to promote students and helping them to become good researchers."

Interdisciplinary collaborations
Bhatotia collaborates closely with the groups of Prof. Christoph Fetzer (Systems Engineering), Prof. Hermann Härtig (Operating Systems), Prof. Wolfgang Lehner (Databases), and Prof. Thorsten Strufe (Privacy and Data Security). Another potential collaborator is Professor Jeronimo Castrillon. The close-knit network of various scientific fields in Dresden enables Bhatotia to work interdisciplinary: initial ideas were exchanged with biologists, e.g., Prof. Gene Myers from the Max Planck Institute for Cell Biology and Genetics (MPI-CBG). The investigation of genetics today faces similar problems computer scientists were confronted with recently and some of their solutions are considered useful for biologists. Today, biologists focus on the same scales and deal with the same amount of data as computer scientists, so cooperation seems necessary.

Outlook
In the next three to five years, computing units will become more advanced owing to the developing processors and the question is how this effects the entire software stack. These complex heterogeneous systems need to be protected against software bugs which is crucial for dependable software. Personally, Bhatotia strives to be one of the leaders within the computer systems community: "I will be glad to see my results being recognized by the people or peers I am respecting! Also, accepting a call for a full professorship within the next five years would precisely match my goals."

Path: Resilience

MARTIN CLAUS
cfaed Research Group Device Modeling for Emerging Electronics

What is the trait you most deplore in yourself?
To be impatient with my students
What would your super power be?
To change real objects just by telepathy
What did you want to be when you were growing up?
A chef in a small restaurant
What makes a perfect day for you?
Sitting with my notebook in the garden working in the sun
What fascinates you most about the job?
To work together with brilliant people

Research
Dr. Martin Claus' research focuses on modeling and simulation of transistors. If an electrical engineer wants to design a complex system such as chips for mobile communication consisting of hundreds of millions of transistors, he needs to run many simulations for optimizing the system. The computer needs to know the behavior of a single transistor in form of a so-called compact model which is a set of equations and parameters. "My research is partially focused on the development of these equations for transistors built up from different materials. The challenge is to simplify very complex physical descriptions behind the transistor's working principles into a set of easily understandable equations still capturing its substantial physics." describes Claus. "Although the results of our work are needed everywhere, the worldwide modeling community is very small. The models one group develops can be applied by thousands of people and groups. For example, the model we designed for the CNTFETs (Carbon Nanotube Transistors) is used by Prof. Ellinger's team at TU Dresden, but can also be employed by IBM, Stanford, and other groups and institutions worldwide."

Exploring carbon nanotube transistors – a multiscale modeling approach
Since CNTFETs represent a very new technology there are still plenty of open questions from an engineering point of view. The goal is to design and fabricate CNTFETs exploring their unique intrinsic features which are not available in other technologies. It is known from theory that these devices can operate at very high frequencies offering at the same time distortion-less signal amplification. These two properties are very appealing for application engineers since both properties would open the market for CNTFETs. A tight cooperative work with the technology group is necessary to provide access to these features. The compact model should predict the CNTFET behavior including their unique properties. By means of circuit simulations, the behavior of the whole circuit is calculated. The intention is that after the fabrication of the circuits, they will behave like predicted in the simulations.

Dresden and Chemnitz unite their strengths
In addition to the excellent modeling team, the Carbon Path also includes a very strong technology group with members from TU Dresden, TU Chemnitz, and Fraunhofer ENAS. Claus points out that this research power makes cfaed unique: "We have experts on every modeling level and we have the technology group in one cluster. This environment is one of the prerequisites for the creativity we need to push the research and get rid of the road blockers towards a competitive CNTFET technology. In 2012, the Chemnitz technology group started in the field of high-frequency transistors from zero, but with a lot of experience on CNT processes. Within two and a half years they have succeeded to set up a technology reaching almost the performance in terms of speed of the worldwide best CNTFETs fabricated so far!"

Personal story
During his diploma studies, a lecture about semiconductor physics deeply impressed Claus. He started working on devices as a student research assistant. When he started to work on his PhD thesis in 2006, his supervisor Prof. Michael Schröter offered him this topic triggered by a collaboration with an US start-up company trying to fabricate CNTFETs for high-frequency applications. Since 2013, Claus has been research group leader mainly focusing on the CNTFET technology. He and his group also investigate other technologies such as organic and nanowire FETs and some new topics will move into the group's focus in the next years.
In 2014, Claus was invited to strengthen the international profile of the Universidade de Brasília (Brazil): "This is a unique opportunity to independently teach graduate courses covering fascinating aspects of my research." Since April 2016, Claus has been visiting research scholar at Stanford University (USA) focusing on stretchable electronics.

Path: Carbon

MEIK DÖRPINGHAUS
cfaed Research Group Information and System Theory

What would your super power be?
I'm too rational to think about this question.
What did you want to be when you were growing up?
A pilot like every little boy...it's technique, engineering, metereology, and the emotions while being at an airport...being connected to the whole world!
Later I got interested in scientific stuff and discovered that doing research and teaching people is super fun to me. Bringing your own ideas to other people means having impact.
What is your favorite App on your mobile?
The messaging app – my wife is on the other side of the world! Games are getting quickly boring.

Research
Dr. Meik Dörpinghaus' scientific background is information and communication theory. Thus, his work aims at understanding optimal strategies of information transmission and processing. It is a basic principle of data transmission: The closer a system operates to capacity, i.e., the maximum possible amount of information that can be transmitted in a given time almost error free, the more difficult it is for the receiver to guess the transmitted message. The decoding problem is a decision making problem. Currently, one of Dörpinghaus' aims is a deeper understanding of the behavior of sequential decision making.

Method and first results
Reliable data transmission is also an important topic in the context of the CRC HAEC. During the second funding phase of HAEC, Dörpinghaus with his group investigates feedback-based coding schemes to enable reliable communication over wireless links between processor nodes on different circuit boards in future servers. Communication here has to fulfill very strict latency requirements. Reliable communication can be achieved with forward error correction codes. "In that way, we are able to decode with a very low latency (100 nanoseconds)" Dörpinghaus says. If there is in addition a feedback link, it might help to further decrease the latency, or make communication even more energy efficient and reliable. Latency can be even more reduced if the receiver decides on the fly what it believes the transmitter sent, i.e., using sequential decision making. Although sequential decision making has already been introduced at the end of World War II, there are still many open questions from an information theoretic point of view, providing a lot of room for further investigations and new results.
A moving cell phone observes a wireless channel with permanently changing quality. The dynamic of these changes depends on the speed of movement, e.g., it is higher when moving in a fast train in comparison to a walking pedestrian. This dynamic has a direct impact on the channel capacity. In recent years there has been a lot of effort to characterize this capacity. While most of these works are based on a standard symbol rate sampling channel model, Dörpinghaus found out that this model does not sufficiently reflect the behavior of the actual continuous-time channel. The study of the capacity of the continuous-time channel is mathematically very challenging, but some progress has already been made. A first paper on this topic was quickly accepted for publication in the 'IEEE Transactions on Information Theory'. In only four months, the paper was published; on average it takes two years from submission to publication in this journal.

Interdisciplinary approach
cfaed's interdisciplinary network is highly appreciated by Dörpinghaus: "I am contributing my knowledge to the Bio and HAEC Research Paths, which I am involved in. The connections to other scientific areas are a major advantage of cfaed. In a joint work with scientists from MPI-PKS we recently had some really good results. We connected sequential decision making with statistical thermodynamics (entropy production), which was fundamental and unknown before – and we would not have achieved this without the collaborations within the Cluster."
Within the CRC HAEC, Dörpinghaus currently concentrates on the design of optimal communication schemes and coordinates the activities of the projects related to the new communication architecture. After his return from a six months research stay at Stanford with Tsachy Weissman, Dörpinghaus will further pursue his research vision including new ideas gained abroad and plans to further grow his group.

Personal story
Dörpinghaus' scientific interest has always been twofold and he had to make a decision whether to concentrate his studies on electrical engineering or physics. He is fascinated by the discovery-driven natural sciences as well as by the innovation-driven approach of engineering. During his pre-diploma of physics, Dörpinghaus acquired useful analytical skills which he still uses today. He finally decided to stay with electrical engineering and received his PhD from RWTH Aachen University with a thesis in the area of information theory. After joining the CRC 912 HAEC as a group leader, Dörpinghaus gained an interest in the interdisciplinary work of cfaed giving him the chance to revive his twofold scientific curiosity.

Path: HAEC

MARTIN ELSTNER
cfaed Research Group Chemical Information Processing

What is the trait you most deplore in yourself?
I have to confess that I am a chocoholic!
What would your super power be?
To be invisible
What is top of your bucket list?
A "Nature" Paper ☺
What makes a perfect day for you?
Eating ice cream
What is your favorite App?
Nerd-Reply: Evernote / otherwise: Angry Birds
Describe the most important research achievement/ invention ever?
Fridge

Research
Dr. Martin Elstner's Group investigates information processing being operated by chemicals. This means, that data is not transmitted by electrons like in standard electronical systems. The background of this approach is that chemicals are considered being good substitutes to today's solutions in some specific application areas. Automated medical diagnostics or laboratory tests represent a big group amongst them. Once, diagnostic devices could act really autonomously where no control from another external machine would be necessary. This means a big improvement in the area of point-of-care diagnostics. Another field of action are hybrid systems which combine chemical information processing and standard computers. Some difficult operations constitute a big challenge to silicon computers. In future, they could be processed by chemicals, and after that the standard computer takes over and combines all these heterogeneous results. This is understood as complementing of classic systems by new technologies.

Method and first results
"We use a simple approach which gives us the opportunity to quickly build prototypes and this results in easy to handle machines. Such a hands-on approach – 'let's go to lab, build a machine and see if it works' – allows us to prove the functionality of different desired operations and go on to develop more complex machines in the next steps," Elstner says about the working mode of his group. Accordingly, they developed a 'sugar computer' based on saccharides like glucose or fructose which do some standard operations like multiplication and addition. In general, the processing is based on several types of inputs from chemical reactions. Operating with large molecule groups in a parallel way can increase the throughput. If two substances are mixed, a chemical reaction or no reaction will happen. In case of a reaction it produces an output that can be monitored. Such signs of a reaction, for instance, could be emitted light or volume changes. This chemical force can be used to control things like micro switches or the optical properties of a material. All information processing is based on some logical operators like AND, OR, NOT. Elstner's group uses the IMP (implication logic) type of a logic gate. These IMP gates are computational complete – every desired chip can be designed only of IMP gates. The same applies to the NAND gate (NOT AND) often used in microelectronic chip design. In today's electronics IMP logic can be hardly implemented, but chemical computers are able to work with them. "We implement the IMP gates in our systems, this enables us to build every other logic gate out of them. So, every problem solvable by a computer is also solvable by chemical computers!" Elstner explains.
The next achievement on the sugar computer was the 'chemical game': "We can play tic tac toe with the chemical computer! The game is based on fluorescent output. We use three different colors depending on the player's move, the output is a specific pattern which can be recognized by naked eye." The chemical reaction is very quick: it takes less than one second so that a real game is possible. Though these first positive results are done, there is still a long way to go. Elstner expects a range of time by 10 years until autonomous information processing in medical diagnostics will be on the market. Also the hybrid systems with complemented electronic computers for special purposes will take that time or even longer to be implemented in everyday applications.

Personal note
Elstner studied chemistry at the Friedrich-Schiller-University, Jena but also developed an interest in biological topics and focused on analytical chemistry and spectroscopy. His thesis 'Molecular logic at single molecule level' pushed him into the applications and information processing direction. However, this approach is influenced by physical conditions such as the Heisenberg's uncertainty principle, so another approach would be more much more useful: Elstner shifted his focus to the use of large groups of molecules. This happened when he first met Prof. Andreas Richter. They stayed in touch and Elstner applied for the group leader position at cfaed right after his PhD which he gained under Prof. A. Schiller in Jena.

Path: CIP

SASCHA HERMANN
cfaed Research Group Carbon Nano Devices

What is the trait you most deplore in yourself?
Restlessness and impatience
What would your super power be?
Give me a technological problem and you get a solution.
What makes a perfect day for you?
At work – interesting results and a motivated team
At home – smile from my daughter and wife
What place feels like home for you?
Scientific laboratory with fancy equipment
What fascinates you most about your job?
Being able to achieve superior and noticeable effects by manipulating the matter at its smallest level with your hands

Research
"A smartphone which consumes significantly less power than current ones or ultra-sensitive sensors which may be integrated in an artificial sensor skin – these are some of the visions that drive me and my group Carbon Nano Devices", Sascha states. Unfortunately, Carbon Nanotubes (CNT) have one big problem: making use of the intrinsic properties on the basis of industrial compatible integration technologies remains extremely challenging. Thus, it is high time to bridge the gap between science and application for this nanomaterial: "Our work contributes to this open topic with a unique holistic wafer-level approach. This enables to move up the technology readiness ladder by demonstrating technologies for CNT devices such as high-frequency transistors."

Application of carbon nanotubes – a wafer-level approach
Aiming at a reliable technology platform for CNT integration requires to consider all aspects in the fabrication chain starting from tailoring material properties to site-selective assembly of CNTs and culminating in CNT device fabrication including crucial steps such as contact formation. In general, the group uses single-walled CNTs (SWCNTs) that are only about 1 nm in diameter and a few 100 nm long. Although a few companies offer high purity and type-enriched SWCNTs, there is still a mismatch between available CNT properties and requirements from application as well as technology perspective. To tackle this issue, Sascha's group implemented methods such as length separation of high-grade type-enriched CNTs in their process flow. Moreover, growth processes on wafer substrates by chemical vapor deposition were developed. For the assembly of CNTs, Sascha has developed a very flexible wafer-level processing system based on the dielectrophoresis method. "Today we have a tool which allows us to localize presorted CNTs with a certain density and alignment even in large and dense device arrays on wafer-scale. Moreover, we gained important insights by means of in-situ process monitoring enabling to see assemblies even down to single-tube level in real-time." Sascha's group uses the excellent R&D environment and clean rooms at the Center for Microtechnologies at TU Chemnitz and Fraunhofer ENAS.

Dresden and Chemnitz unite their strengths
Sascha's project uniquely unites science, modeling and technology competences at Dresden and Chemnitz towards realizing CNT-based high frequency transistors and circuits. The wafer process line at Chemnitz and the synergies arising from the combination of university research in Saxony as well industry related R&D of institutes such as Fraunhofer ENAS, enabled to establish a technology platform for nano devices on wafer-scale. Thereby, this platform is not only applicable for integration of CNTs but also for other nanomaterials of interest. Only a few groups world-wide work on such an approach. In Europe Sascha's group is the only one.

Personal story
Driven by an interdisciplinary thinking as an applied physicist and engineer, Sascha's fascination of the potential of CNTs started in 2006. He accepted a PhD position in the international research training group on Materials for Advanced Interconnects in Prof. Stefan Schulz`s department at the Center for Microtechnologies headed by Prof. Thomas Gessner. His task was very challenging: fighting for persisting of Moore`s Law by implementation of CNT interconnects in ULSI circuits. Starting from zero on the CNT-topic at this institute, Sascha finally managed to grow CNTs in a controlled manner and integrate CNTs as interconnects after a couple of years. In parallel, Sascha started to play with alternative methods for CNT integration such as the dielectrophoretic assembly of CNTs. Although it is a well-known method in biology, it was far from being applicable on wafer-level for nanomaterials like CNTs. In particular, the latter fact and the idea to have control over assembly of these tiny nanostructures motivated Sascha to develop the tools and the method further. Today, he has reached a level where he is able to talk about a deposition system and a complex but controllable process for assembly of CNTs. "All of our different projects would not be possible without a strong group behind me," Sascha says gratefully.

Path: Carbon

THORSTEN SCHMIDT
cfaed Research Group DNA Chemistry

What makes a perfect day for you?
Of course there are some great lab days, but in general it would be sleeping in, then playing with my son, having a nice breakfast, eating out at our favorite Indian restaurant, going running in the afternoon.
What fascinates you most about the job?
Freedom – the freedom that I can do what I like with whom I like when I like. This you don't have in many other jobs...
Three things few people know about you?
I'm a good salsa dancer. I speak this ancient German language called 'Siebenbürgisch-Sächsisch' (Transylvanian Saxon dialect). As a pupil, I wanted to become a writer, I wrote some short stories that time.

Research
In the field of DNA Nanotechnology, Dr. Thorsten-Lars Schmidt's group occupies a small niche topic. Widely investigated are the drug delivery for nanomedical applications, storage of information in DNA or biophysical phenomena, but only a few others explore optoelectronic devices. Schmidt's group 'DNA Chemistry' at cfaed investigates structural DNA nanotechnology to build self-assembled devices for optical short-range (such as on-chip) communication. These could be integrated in future optoelectronic components with increased communication bandwidth.

Amazing building material
DNA is a unique building material for nanometer-sized structures, since it is one of the best understood and most programmable polymers. These programmable interactions can be used to produce nanometer-sized structures with almost arbitrary shapes that do not occur in nature. With this technique, flat squares, elongated tubes, hollow boxes or even smiley faces can be produced that are several thousand times smaller than the diameter of a human hair.

From complex DNA structures to plasmonic waveguides
Various molecules such as fluorescent dyes, proteins or nanomaterials like metallic nanoparticles can now be bound at any predetermined place on the surface of the DNA nano-architectures. This way, a much higher positioning precision of a larger variety of materials can be achieved than with any other method. Schmidt's lab at cfaed aims at developing self-assembled 'plasmonic waveguides', which can guide light similar to a glass fiber. Their waveguides are, however, much thinner. Such plasmonic waveguides can consist of gold nanoparticles positioned like pearls on a necklace along a DNA scaffold. The nanoparticles are significantly smaller than the wavelength of light, which is crucial for a possible use in information technology. "We want to integrate optics into microelectronics which is very challenging because the sizes of classical optical components such as glass fibers are in the millimeter range, whereas silicon electronic components are on the nanoscale – this is like trying to glue a tree to a hair" says Schmidt.

Next steps – progress through collaboration
"As we have started only two years ago we are still at an early stage. We are able to arrange the gold nanoparticles on DNA nanostructures with higher yields than any other group so far. Now we have to prove that our self-assembled structures are functional and guide light. This is a very complex task and we therefore collaborate with several groups inside and outside cfaed" Schmidt summarizes. One challenge will be to minimize the transmission losses. Theoretical calculations are now being performed at the Leibniz Institute for Polymer Research (IPF) to optimize the geometries of the arrangements. Next, the waveguides have to be transferred from aqueous solutions to surfaces such as silicon wafers to create sophisticated networks and functional devices. After a successful alignment, they have to be contacted. Schmidt's group cooperates with many different laboratories in the region and worldwide, e.g., HZDR, IPF, Fraunhofer IZI Leipzig, CRTD, and inside TU Dresden shares machines and knowledge with both the Mertig and the Eychmüller groups, as well as the BIOTEC.

Personal story
Schmidt's career has already taken quite a few steps. Being born in Romania, he moved with his family to Germany at the age of six. After studying chemistry in Bonn, Oviedo (Spain) and New York, he received his doctorate with distinction in Frankfurt (Main) and then he completed a nearly 3-year postdoctoral research stay at the Wyss Institute for Biologically Inspired Engineering at Harvard in Boston before he joined cfaed.
DNA nanotechnology played a role even in his private life: In the course of his PhD thesis he developed a 'DNA-glue'. Later on, using this glue, Schmidt synthesized two interlocked rings of DNA and gave a drop of water containing a few billion copies to his wife as a wedding present. Since the rings were only 20 nanometers in size, they were probably the smallest wedding rings in the world. "She is also a scientist and really appreciated this gift" Schmidt recalls.

Path: BAC

WALTER WEBER
cfaed Nanowire Research Group

Which living person do you most admire and why?
People that engage themselves in difficult social situations, risking their lives, taking care of integrating people from somewhere else in regions where there's not such a tradition for it, but I wouldn't name anyone specifically.
What would your super power be?
Make people talk to each other & understand each other
What makes a perfect day for you?
Waking up and seeing my children and wife
Three things few people know about you?
I'm Mexican. I like mountain-climbing and ski-mountaineering, I don't have fun with normal skiing (too many people, boring artificial & prepared snow).

Research
Dr. Walter M. Weber's group investigates electronic devices that are to be implemented beyond conventional CMOS switches. The group is looking for unconventional solutions enabled by silicon and germanium nanowires (SiNW and GeNWs) to deliver electronic devices that can do much more than a regular switch. Conventional electronic devices have simple functions, they can only be turned on and off. Weber's group is aiming at devices with an increased functionality space, based on unique electronic properties of the extremely small nanowires. These properties enable novel devices, which can be used to build revolutionary circuits and systems. The group's research spans all levels: starting with the materials, including devices, circuits and culminating in systems.

First breakthroughs
"To produce the nanowires we apply two complementary approaches: 1) We either synthetically grow them as crystals and print them on host substrates; or 2) we pattern the nanowire structures via lithography and anisotropic etching which is the more conventional method," Weber explains. The SiNW are small scale objects: their cross-section comprises a diameter of down to 12 silicon atoms. "These ultra-small structures have different properties compared to 'bulk' silicon: as the charge carriers have little room to move in these transistors, it's very simple to control them. By applying mechanical strain, we even gain electronic effects, which cause the same conductance between electrons and positively charged holes." The team has conceived new types of devices merging different functionalities, namely 'reconfigurable transistors' (RFETs). They can produce and tune them in such a way that real circuits can be made out of them. Such RFETs enable a 'Single-MOS technology' combining the p and n types of today's transistors to one device that can provide both functionalities on demand. An enormous simplification in technology, and the ability to modify the transistor function at runtime allows to condense complex functions into fewer transistors. For specific logic functions, an advantage in circuit area, power consumption, and sometimes in speed can be achieved. In general, the SiNW devices are expected to be incomparably inexpensive and the processing steps are simple and even transferable to flexible plastic substrates.

Outlook
Based on the same material combinations, future SiNWs and GeNWs can be heterogeneously integrated with conventional CMOS technology. Another target is to control the energy consumption of each single electronic device inside a system – so that particular circuit elements will run on high performance only when needed. This could be very interesting for, e.g., portable devices where a tradeoff between performance and low power consumption is needed. Weber investigates the complete development chain up to real applications in order to attract the industry. To fulfill these goals, the scientists also have to cooperate with software engineers. "Scientists from different disciplines also have a different philosophy of approaching a given problem. Putting this together with the individual scientific knowledge really broadens our horizon," finds Weber. "My team works with many cooperation partners inside and outside cfaed, e.g., with experts in sensing and materials scientists around Prof. Gianaurelio Cuniberti, with biologists, and chemists." The Orchestration Path investigates the effects of the SiNW devices on a large scale. There is also important cooperation with the physics departments at HZDR, the HZDR Nanonet research school, and the IFW. The Dresden Center for Nanoanalysis (DCN) is also an important partner for Weber's team.

Personal Notes
"I grew up in Mexico and went to a German school. During my studies of Electrical Engineering I moved to Munich, which was the first time I experienced Germany by myself. I received my PhD from TU Munich but the research was performed at the Infineon AG and Qimonda AG." Weber's focus was on the synthesis of nanowires heterostructures and the conception of novel nanowire based transistors with programmable polarity. Since 2008, he is a Senior Scientist at NaMLab gGmbH leading activities on Beyond-Moore emerging devices and circuits. "I think it's important not to become a 'blinkered specialist'. One has to be open to intermix disciplines. Of course I would like to stay in Dresden, but I'm a flexible person and also very open to other places, including a move back to Mexico."

Path: Silicon Nanowire

MARCO ZIMMERLING
cfaed Research Group Networked Embedded Systems

What is top of your bucket list?
Run the New York City Marathon
What is your favorite food?
Sushi
What fascinates you most about your job?
Teaching and working with smart people (especially students) on challenging problems
What do only a few people know about you?
When I'm not in front of my computer, I enjoy my three children as well as long-distance running, cooking, fishing, hiking, reading books; sometimes, I also dust off my stamp collection.

Research
Dr. Marco Zimmerling and his group work at the interface of embedded systems and wireless networking. They aim at building wireless communication and runtime systems that power future Cyber-physical Systems (CPS) applications. The transformative power of CPS arises from the integration of sensors, actuators, and computing elements into feedback loops, enabling CPS to directly control the physical world. The use of tiny battery-powered devices with low-power radios and microcontrollers promises increased flexibility, scalability, and efficiency at lower costs. To reap these benefits while supporting mission-critical CPS applications, the wireless networking substrate must be predictable, adaptive, and operate efficiently. Meeting these requirements presents a huge challenge given the unpredictable, non-deterministic, and resource-constrained nature of low-power wireless networks.

Approach
Zimmerling takes a radically different approach: rather than trying to avoid packet collisions, the group develops novel protocols that deliberately force packet collisions. By exploiting these so-called synchronous transmissions, it becomes possible to design protocols whose logic is independent of the network state (e.g., link qualities). As a result, the protocols adapt instantaneously to the network dynamics. Using network-wide synchronous transmissions as the only means of communication, Zimmerling has designed a globally time-triggered protocol, where all devices communicate according to a single global schedule. This reduces the amount of concurrency in the network compared to the distributed and uncoordinated operation of existing protocols, enabling highly accurate predictions on the future behavior and end-to-end performance of the network.

Results
By adopting this approach, Zimmerling has essentially built a 'wireless bus', where all nodes can receive all messages. The wireless bus provides a view to upper layers that the entire network is a single entity that runs on a single clock. Moreover, the way communication occurs over the wireless bus is completely orthogonal to how the global schedule is computed. Thus, the bus scheduler is a pluggable component that can be tailored to the needs of the application. Zimmerling has already developed several wireless bus systems that use different schedulers and practically demonstrate functionality that either solves an important problem that remained unsolved for over a decade – providing hard end-to-end real-time guarantees across a multi-hop low-power wireless network – or was previously considered impossible to achieve – providing virtual-synchrony based group communication and coordination.

Outlook
In future, the group will focus on three lines of work. First, there is still a significant lack of understanding of the underlying synchronous transmission technique. To fill this gap, fundamental work exploiting theoretical analyses and controlled real-world experiments will be conducted. Second, based on the insights gained, the group will conceive ways to significantly boost the reliability of synchronous transmissions, and explore ways to increase the capacity of the protocols that make use of them. The envisioned improvements will benefit all higher-layer functionality. Finally, the group will work with experts in automation and control to demonstrate for the first time the feasibility of closed-loop control over a wireless multi-hop network with controller update rates in the 100 ms range. To support the development of the corresponding CPS applications, they will also work on embedded platforms and programming models that simplify development while enabling verification.

Personal note
Zimmerling has been a Research Group Leader within cfaed since November 2015. He completed his PhD at ETH Zurich in the Computer Engineering Group headed by Prof. Lothar Thiele and holds a diploma degree in computer science from TU Dresden. Therefore, joining cfaed was like 'coming home' for Zimmerling. During the write-up of his diploma thesis and studies, he spent six months in Sweden visiting SICS Swedish ICT, Kista (near Stockholm) and Uppsala University, and interned for 14 months at IBM, including a six-month stay at the well-known T.J. Watson Lab in Hawthorne, NY, USA.

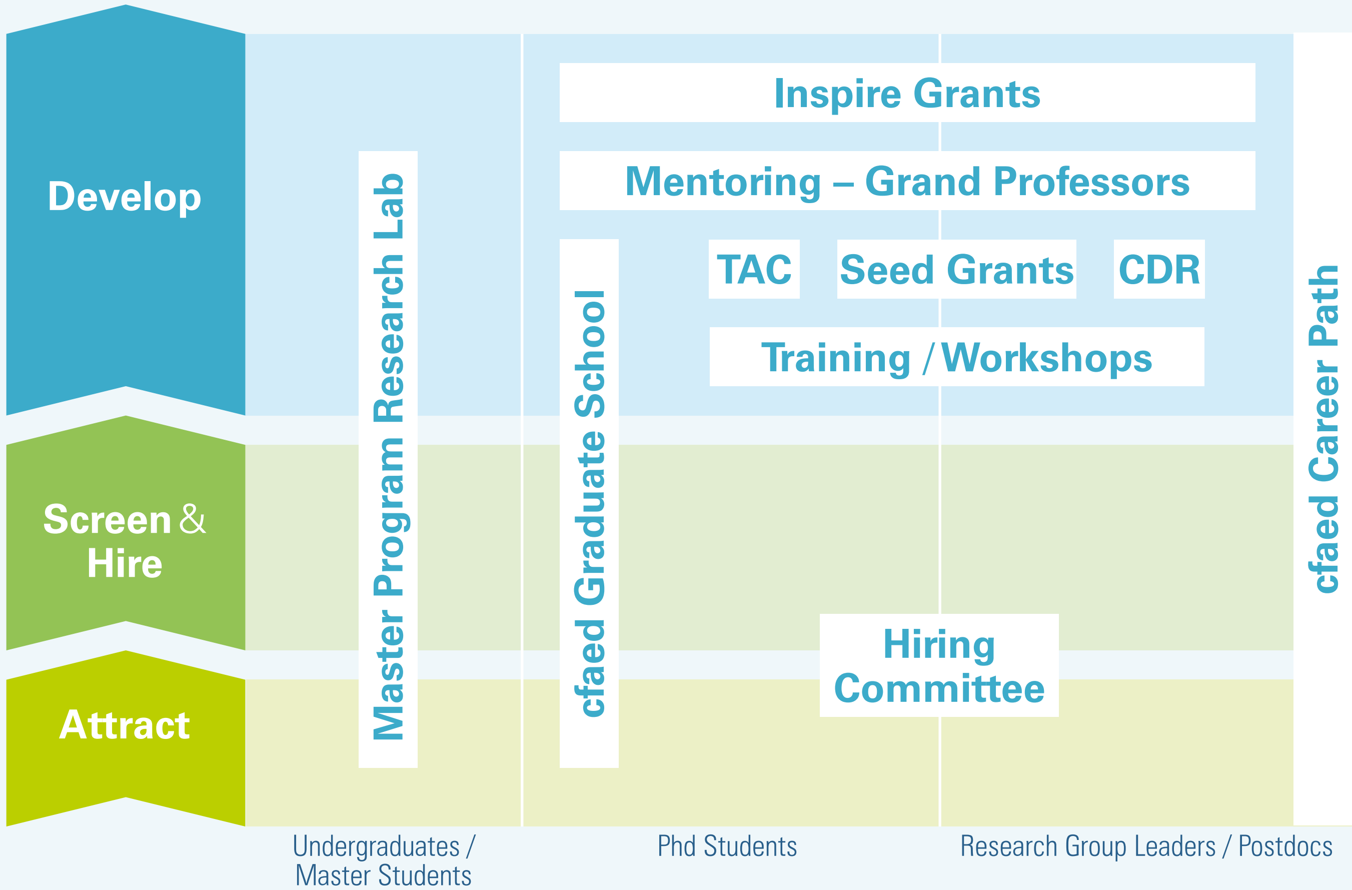
Path: Resilience

"It is possible for you to realise your dream as a scientist, you must be a passionate learner and curious enough to seek this wonderful career path."

Lailah Gifty Akita

Career Development Program

cfaed has developed an exemplary, structured career development program with the purpose of supporting and guiding young scientists throughout their scientific career. Establishing career development as a standard tool for all career levels in academia, comparable to the common practice in industry, is an ambitious goal of cfaed's postgraduate program. The program aims at developing cfaed's PhD students, Postdocs, Research Group Leaders, and young Professors into innovative minds, groundbreaking researchers, and inspiring educators. cfaed's Career Development Program is designed to provide young scientists with the necessary tools to establish a successful career. Participating in the program ensures that cfaed members are equipped with the academic knowledge and career management skills to be successful either in a scientific career or within industry, depending on individual ambitions and potential. From one-to-one meetings with mentors to regular feedback sessions with advice on a long-term career plan, the program gives ample opportunity to carve individual career paths.



Comprehensive Career Development Approach

Attracting and forming young international researchers is of utmost importance to cfaed. Not only does the large research program require a high number of well qualified and highly motivated young researchers, but also these young people will provide the foundation to sustain cfaed far beyond the initial funding period. Furthermore, cfaed seeks to generate a strong output of superbly trained experts and will also in this respect meet societal expectations. To achieve this, cfaed relies on three key features: (I) attractiveness through highly challenging research topics; (II) an inspiring scientific environment; (III) through a systematic career development allowing young researchers to progress quickly. The program helps young scientists emerge as leaders through mentorship and advice. As cfaed considers the career development as one of its most important organizational tasks, a dedicated HR team supports the appointment processes for the Strategic cfaed Professors, the selection of Research Group Leaders as well as PhD students for all cfaed groups. Support mechanisms span all issues from recruiting new group members to general administrative issues. By December 2015, cfaed had recruited more than 130 scientists from more than 20 countries. Until early 2016, two of cfaed's previous Research Group Leaders had moved on to attractive positions at the University of Luxembourg and a Helmholtz Centre in Braunschweig. Nurturing researchers so that they are able to live up to their fullest potential is supported by trainings and courses with the aim of sharpening academic skills, such as writing excellent theses and publications as well sensitizing the awareness for social and communication skills. Despite various measures to win and keep women in science cfaed has to realize that only nearly a quarter of all hired scientists are women and the Cluster was not successful to attract women to group leader level upwards. Several ideas are currently being investigated to improve this situation.

Career Development Director

cfaed Career Development Director since 2015: Prof. Karl Leo (Chair for Optoelectronics, TU Dresden)

Former (2012-2015) cfaed Career Development Director: Prof. Alexander Eychmüller (Chair for Physical Chemistry, TU Dresden)

The cfaed Career Development Director is responsible for all matters concerning recruitment, career development, and mentoring as well as for the planning of individual programs for career enhancement based on the young scientists' strengths and needs. The role holder is a member of the Cluster's Executive Board and functions as the Cluster's Deputy Coordinator.
The position is a rotating role amongst cfaed's Principal Investigators and their experience as researchers, teachers, and mentors support the discussions about the program and help to shape and define ideas such as the annual review of the Cluster's PhD students and Research Group Leaders.

Graduate School

The structured Career Development Program includes a cfaed Graduate School with the following main aspects:

Individual Development Reviews
- for PhD students: Thesis Advisory Committees
- for Research Group Leaders: Career Development Reviews

Training Modules
- e.g., general, path specific, personal trainings

Special Programs:
- Mentoring
- Grand Professors
- INSPIRE Grants
- Seed Grants

The Individual Development Reviews aim at supporting and encouraging young scientists in their current projects and the development of their career. The **Thesis Advisory Committee (TAC)** is dedicated to PhD students and helps them to monitor and evaluate the progress of their research project. The TAC comprises three supervisors and meets at least once per year. One of the supervisors acts as peer reviewer throughout the PhD period. After the initial planning phase, the TAC program was implemented in 2014.

For all Research Group Leaders (RGLs), the **Career Development Review (CDR)** has been implemented. Two supervising professors and the cfaed Career Development Director participate in this annual meeting and provide the RGLs with independent opinions about their scientific and personal progress. Recommendations for further improvement in the areas of scientific visibility and involvement, individual trainings, supervision, third party funding, mobility as well as personal and communication skills are provided to the RGLs. Senior researchers of cfaed have shared their experiences to support the RGLs by communicating clearly the essential requirements for climbing up the academic career ladder and becoming a professor. The CDR is now an established instrument for both, RGLs and supervising professors.

The **Training Modules** aim at providing additional competencies and professional orientation. Topics of the workshops target the specific needs of the Clusters' young scientists that are discussed during the TACs and CDRs. The trainers are chosen carefully by the Career Development Team and must meet several requirements, e.g., proficiency of English, academic and industry background/experience. Regular workshops on generic research expertise, soft, and management skills are targeted.

Workshop Overview

Generic Research Expertise
- Proposal Writing for Young Researchers
- Research Funding Using the Example of DFG´s Research Grants Program
- Extramural Funding - Key Factors for Success
- Enhance Your Teaching Competence: The Basics of Learner-Oriented and Activating Teaching Practice
- Poster Making
- Scientific Writing
- Appointment Training for Future Professors

Management Skills
- Project Management
- Leadership Skills for Researchers
- Reflecting Leadership

Soft Skills
- Networking for Scientists
- Presentation Training

Statement RGLs

"cfaed takes career development seriously. The individual yearly reviews with the involvement of an external mentor and career development director have helped me to sharpen my scientific profile. I get excellent and fast advice to my inquiries from the colleagues from the career development office which is staffed with highly experienced and motivated personal. The combination of the career development courses and the individual mentoring offered really strengthens the development perspectives of the post-doctoral scientists involved."
Walter Weber, RGL 'Nanowire Research'

"The career development courses of cfaed are outstanding. I particularly enjoyed the workshops specifically created for us. People in group leader positions all have some idea how to do research, but at least I had little knowledge how to build and lead a team in a structured way, how to solve conflicts, what university didactics is about – in summary, how to be a group leader. Also, it was great to get some training for the appointment committees. I am sure that many established investigators would have loved to get a comparable training."
Thorsten-Lars Schmidt, RGL 'DNA Chemistry'

"Academia has become a competitive landscape, not only within the individual disciplines but also across disciplines. cfaed's Career Development and in particular the career development reviews have been the ideal instrument for me to learn about this competitive field and its requirements. Within two years, my publication count accelerated and I received scientific visibility, not only in my discipline."
Marcus Völp, RGL Orchestration 2013 to 2015
now University of Luxembourg

"The career development program of cfaed provides a very good framework for succeeding in my own academic career. Especially the career development review meetings are very important, as the professors in these meetings give very valuable advice. I personally liked very much the leadership workshop and also the Appointment Training for Future Professors."
Meik Dörpinghaus, RGL HAEC

Inspire Grants

Every cfaed PhD student and Postdoc can apply for a cfaed INSPIRE Grant which financially supports individual research stays abroad that may take between three weeks and six months. This format fosters the lively scientific exchange, gives the young scientists the chance to gain inspiration for new research topics, and to establish themselves in the international research community. In turn, cfaed benefits enormously by this scientific exchange: the grantees help to increase the international reputation of the Cluster and promote it at other top-notch institutions.

In 2015 and 2016, the following exchanges were supported by cfaed INSPIRE grants:

Dr. Ihsan Amin, Organic Path
12/2014-04/2015, Cornell University, Ithaca, USA

Tim Erdmann, Organic Path
03-06/2015, Northwestern University, Evanston, USA

Dr. Susanne Leubner, BAC/CIP Path
03-06/2015, Arizona State University, USA

Jun.-Prof. Kambiz Jamshidi, HAEC
Summer 2015, Stanford and Harvard University, USA

Jana Kalbacova, Carbon Path
04-06/2015, NIST, Gaithersburg, USA

Dipjyoti Deb, SiNW Path
05-06/2015, Tyndall National Institute, Cork, Ireland

Sayanti Banerjee, SiNW Path
07-11/2015, Institute of Metallurgy and Materials Science, Krakow, Poland

Florian Günther, Organic Path
10-11/2015, University of Sao Paulo, Brazil

Dr. Violetta Sessi, SiNW Path
10-12/2015, RIKEN Quantitative Biology Center, Kobe, Japan

Dr. Artem Fediai, Carbon Path
02-04/2016, King's College, London, UK

Thomas Kämpfe, Carbon Path
03-06/2016, Stanford University, San Francisco, USA

Statements Inspire Grants

"I'm currently working on a paper that is based on the research I did in the US. If it gets accepted, it will be the best outcome of my research stay abroad. Thank you for helping me with the organization of my stay!"
Jana Kalbacova, PhD student, Carbon Path, Inspire Grantee 09/2014

"My work place and colleagues at the University of Krakow were super nice and friendly, and all very helpful. Overall, it was a very satisfying and nice experience, and also scientifically important, best of all worlds! Thanks again for the opportunity!"
Sayanti Banerjee, PhD Student, Silicon Nanowire Path, 3rd year, Inspire Grantee 03/2015

"With my Inspire Grant 2015 I went to Cork's Tyndall National Institute and UCC to push the limit of logic functionalities in a silicon nanowire. It was a successful visit as I achieved to make sub 20 nm silicon nanowires with industry combatable process. Special thanks to cfaed career development team and IHRS NanoNet for funding my trip."
Dipjyoti Deb, PhD Student, Silicon Nanowire Path, 3rd year, Inspire Grantee 03/2015

cfaed Summer School

The cfaed Summer School "Dresden Microelectronics Academy" (DMA) introduced about 40 international Master and PhD students from ten countries to the region's semiconductor industry and the latest results of cfaed's research approach and topics. Owing to the close collaboration of university, non-university research institutions, and industry, the participants had the chance to gain both, practical first-hand and expert knowledge. It is planned to organize the summer school annually and to establish it as a further measure to disseminate cfaed's research and expertise. In addition, master students are introduced to the host institution TU Dresden and often use the summer school as a preparation for their master studies here.

Grand Professor Program

The Mentoring and Grand Professor Program attracted five international experts to join cfaed as personal mentors and to act as collaboration partners in research projects. Especially young scientists benefit from the interaction with them and win long-term mentors to support their careers. All Grand Professors are invited to visit cfaed at least once a year during the Career and Grand Professor Week. During this week, young researchers, cfaed investigators, cfaed Grand Professors, and the Career Development Team come together for various events in different formats. PhD students and postdocs come in close contact with the Grand Professors either by attending scientific talks, in individual mentoring sessions or within social events. Furthermore, the cfaed Career Development Managers introduce the whole Career Development Program to new students, offer individual career consultations, and help with application documents.

Statement Grand Professor Program

"The Grand Professor program is unique to cfaed, and I have recommended it as a model to colleagues and friends at other institutions, including my own. The idea of having successful senior colleagues from around the world to assist in mentoring junior faculty, staff, and students is a great one, and I think it is working well. Certainly those I am involved with seem pleased with the advice I am able to give, and I can see that they have taken advantage of my comments and suggestions each time I visit. In 2015 I was particularly happy to be able to talk with some researchers who are not in my own area of expertise. I think I was able to provide to them some broader perspective and career experience that they can take advantage of, and I could feel that my role as a community elder is very much appreciated in the cfaed community. On every visit I find that I learn from the cfaed community at least as much as they learn from me, and I always go home with inventive new ideas buzzing in my head."
James Cordy, cfaed Grand Professor, Queen's University at Kingston, Canada

Prof. James R. Cordy
Queen's University, Canada

Prof. Hélène Kirchner
INRIA, France

Prof. em. Heinrich Meyr
RWTH Aachen, Germany

Prof. Jan Rabaey
University of California, Berkeley, USA

Prof. Itamar Willner
Hebrew University of Jerusalem, Israel

"One great part of the program for me personally is the opportunity to visit TU Dresden and feel the energy of the place, which is palpable."

Prof. James Cordy,
cfaed Grand Professor

cfaed **Research Team**

TECHNISCHE UNIVERSITÄT DRESDEN

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Prof. Dr. Johann W. Bartha
Chair for Semiconductor Technology

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Head of Department Innovative Methods of Computing

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Chair for BioNanoTools and MPI-CBG

The following members of TU Dresden are part of the Cluster through their membership in the CRC 912

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cfaed Research Group Leader (Carbon Nanotube Integration and Applications)

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Director

MAX PLANCK INSTITUTE FOR THE PHYSICS OF COMPLEX SYSTEMS

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Dr. Anton Kiriy
Head of Department Polymer Structures

Prof. Dr. Jens-Uwe Sommer
Head of Program Area Theory of Polymers, and Professor for Theory of Polymers, TU Dresden

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Institute for Complex Materials

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Institute for Integrative Nanosciences (IIN), and Professor for Material Systems for Nanoelectronics, TU Chemnitz

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Prof. Dr. habil. Ehrenfried Zschech
Division Director Nanomaterials and Nanoanalysis

NAMLAB gGMBH

Prof. Dr.-Ing. Thomas Mikolajick
Director, and Chair for Nanoelectronic Materials, TU Dresden

Dr.-Ing. Walter Weber
Senior Scientist, and cfaed Research Group Leader (Nanowire Research)

Prof. Ralf Seidel
Professor for Molecular Biophysics, University of Leipzig

as of March 2016

Organigram

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Working Together: The New cfaed Building

As an extension to the historic Barkhausen Building, new offices and labs for cfaed will be at the main TU Dresden campus.

Groundbreaking ceremony for the new cfaed building in August 2015

The new Hermann Krone Building of TU Dresden's Institute for Applied Physics will host cfaed labs for nano-structuring.

Under one roof

In May 2015, construction works for the new cfaed building commenced at the campus of TU Dresden. The building is due for completion in late 2017 and it will host new laboratories, seminar rooms, and offices.
cfaed's EUR 35 million facilities will replace one wing of the listed Barkhausen Building, adding two more floors as well as one completely new extension for nano-analytics laboratories.
In total, about 5.000 sqm floor space will be built. Concentrating cfaed's interdisciplinary research activities under one roof will enable a fruitful exchange between the researchers and foster the lively communication between the involved sciences. The completed building will unite what normally does not come together easily: engineers and natural scientists, a listed building and a new extension, young scientists and internationally renowned specialists.
To bridge these aspects is one of cfaed's ambitions.

Central labs

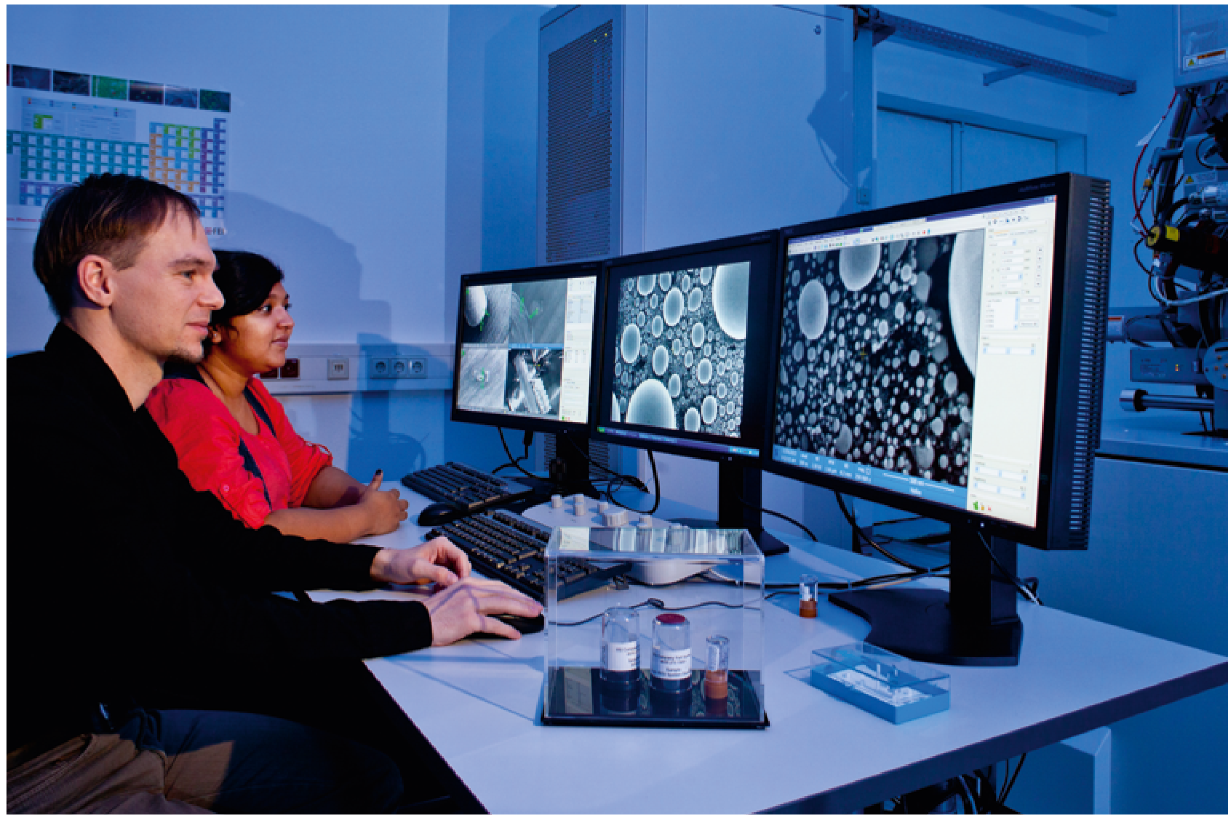
Within the courtyard of the Barkhausen Building, a high-end lab space will be erected to accommodate the Dresden Center for Nanoanalysis (DCN) as central facility. The new labs will have an area of more than 600 sqm including physical, chemical, and biological preparation labs, electronic labs with a physical property measurement system, two low-temperature scanning tunneling microscopes, optical microscopes, and spectrometers and as highlights, two new high-end transmission electron microscopes and one electron beam lithography tool.

Communication

Finally, the new building is intended to support the vivid communication within the Cluster. A communication area will be built with direct access to the neighboring Heinz Schönfeld Lecture Hall, which will be reconstructed in parallel to the construction works at the cfaed building. Hopefully, both will be finished at the same time so the opening of the new facilities can be celebrated with a cfaed Research Festival in the Heinz Schönfeld Lecture Hall.

DCN – Dresden Center for Nanoanalysis
Technological Platform for State-of-the-Art Analytics

With increasing miniaturization of devices, whose behavior may be affected already by individual atoms, and with the incorporation of new and exotic materials such as graphene, a chemical and structural analysis of the components with higher resolution is required to improve and understand these new device structures. More-than-Moore architectures such as Si-Nanowire based reconfigurable transistors (Si-NW RFETs) are just one of the numerous ways to beat the inevitable roadblock that comes in the way of fundamental physical limitations. Also for the development of materials for the harvesting of sustainable energy, nanoanalytics are indispensible, e.g., the morphology of the active layer in organic solar cells has a significant impact on their performance. The DCN focuses on both, the development of methods and the analysis of materials and devices. The tools and methods available in the DCN can be accessed within a technology platform by all users within TU Dresden and the DRESDEN-concept community, and at a later stage they will be offered nationwide and internationally.



Equipment

Currently, the DCN owns a state-of-the-art analytical low-voltage scanning electron microscope (SEM), the ZEISS Gemini 500, and a state-of-the-art dual beam SEM with focused ion beam (FIB), the FEI Helios Nanolab 660. The former is equipped with an Oxford EDX (energy dispersive X-ray spectroscopy) and EBSD (electron backscatter diffraction) system optimized for work at low voltages. This is particularly important for the analysis of nanostructures and sensitive materials (EBSD 5kV+, EDX 150mm^2 detector, 20nm Si-NW Si-L mapping demonstrated). The Zeiss Gemini 500 also features several detectors, such as the energy selective backscatter detector, which allows for energy filtered high resolution backscatter imaging at landing energies as low as a few hundred eV. This enables the differentiation of different compounds in polymer-polymer blends with minimal or even no electron beam damage. The system can also be used in a "vapor pressure mode" that allows for high resolution imaging of specimen that tend to charge. This is achieved through differential pumping and the use of the in-lens rather than electron cascade detectors as it is usually employed in environmental SEMs.

The FEI Helios Nanolab 660 is a flexible tool both in ion beam and in electron beam mode. Its strength is the combination of high resolution imaging with the ability to locally modify the sample on the nanometer to micrometer scale. The ion beam enables the use of local sputtering to either remove material or to image the sample with ions for strong channeling contrast images. Several gas injection systems that can be used in combination with the electron or ion beam allow for enhanced etching (XeF_2) or the controlled deposition of metals (Pt, W) or carbon. The system can also be used with a 5-axis nanoindenter (Hysitron PI87) for in-situ measurements of mechanical properties. The PI87 also allows for simultaneous electrical characterization. In addition, a Kleindiek manipulator is available for the system, including a low-voltage measurement kit for the detection of small voltages or currents through the specimen. This manipulator allows for a more flexible control than the installed EasyLift manipulator, and can be used in conjunction with the latter. A second Kleindiek manipulator will soon be available for the system in order to provide for more degrees of freedom during in-situ measurements.

For the analysis of µm to cm-sized 3D structures, the toolset is complemented by a sub-µm X-ray computed tomography (XCT) system, the Zeiss Versa 520. This system offers substantial flexibility in sample size and enables the user to identify regions of interest in three dimensions. It has been used to characterize failure modes in structures used for the 3D integration of microelectronic chips as well as on micro-opto-electro-mechanical systems (MOEMS).

User Facility

The DCN is not only a research center but also a user facility, where access to the instruments is provided to users, who can receive training and gain hands-on experience. Currently, there are 24 independent users from 4 different research groups. In addition, analysis tasks are performed by DCN staff as a service to users, who are not able or willing to use the instruments on their own.

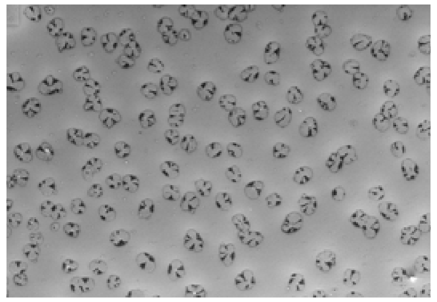
Platform Concept

The paths of the cfaed comprise a variety of facilities for structuring semiconducting materials such as the cleanroom of the Werner Hartmann Zentrum (TUD), the Institute of Semiconductors and Microsystems (TUD), the NaMLab, the Center for Microtechnologies (TUC), and the HZDR.
The DCN provides additional access to state-of-the-art analytics equipment that is either owned by the DCN or offered through participating departments of the TU Dresden and within DRESDEN-concept. The DCN will provide a unified booking and accounting system, and together with its partners, it acts under common and mutually accepted terms of use. Hereby, the DCN not only broadens the nanoanalytical toolset for its members and users, but it also seeks to stimulate and foster collaborations across faculty borders and research disciplines.

Scientific Coordinators:
since 2016 Dr. Bernd Rellinghaus
2013-2015 Prof. Ehrenfried Zschech

www.cfaed.tu-dresden.de/dcn

dcn dresden center for nanoanalysis



SEM image of the mixture of donor and acceptor for organic solar cell on cupper

The same mixture on silicone substrate, being observed with two different detectors

Timeline cfaed Events

2012–2013

Prof. Albert Fert
Nobel Prize Laureate
Université Paris-Sud, France
"Spintronics: Electrons, Spins, Computers and Telephones"

Prof. Moshe Y. Vardi
Rice University, USA
"From Aristotle to the Pentium"

Dr. C. Mohan
IBM Almaden Research Center, USA
"Implications of Storage Class Memories on SW and HW Architectures"

Prof. Carlos Cuevas
UAM, Spain

Prof. D.H. Riesner
Heinrich-Heine-Universität, Düsseldorf
"Viroids and Prions"

Prof. Spencer Sherwin
Imperial College London, UK

Prof. Serge Haroche
Nobel Prize Laureate
Collège de France
"Particle Control in a Quantum World"

Prof. Valeriu Beiu
United Arab Emirates University, UAE

Prof. Christian Schönenberger
University of Basel, CH

2012

DFG Evaluation
of full proposal

Announcement
funding awarded

DFG Visit

2013

Official Opening

Career Development Kick-off

Career Development Fest

2014–2016

Sir Christopher Snowden
University of Surrey, UK
"The Electronic Adventure – Engineering a Better Future"

Prof. Lorenzo Alvisi
UT Austin, USA

Prof. Andrew Mackenzie
MPI CPoS, Dresden

Prof. Thomas Seyller
TU Chemnitz

Prof. Klaus Müllen
MPI for Polymer Research Mainz
"Electronics and Sensing with Organic Nanostructures"

Prof. Victor Klimov
LANL, USA

Dr. Antonia Wachter-Zeh
Technion, Israel

Prof. Shawn Douglas
UCSF, USA

Prof. Claudia Felser *MPI CPoS Dresden*

Prof. Sumio Iijima
Meijo University, Japan
"Structural Characterization of Nanomaterials"

Prof. Assaf Schuster
Technion, Israel

Prof. Stephan Roche
ICN2, Spain

Prof. Andras Kis
EPFL, CH

Prof. Maarten Wegewijs
RWTH Aachen

Prof. Thomas A. Vilgis/ Dr. Brigitta Zielbauer
MPI Polymer Research, Mainz

Prof. Michael Grätzel
EPF Lausanne, CH
"Nanocrystalline Junctions and Mesoscopic Solar Cells"

Dr. Chris Cantwell
ICL, UK

Prof. Carmen Herrmann
Universität Hamburg

Prof. Kensuke Osada
UTokyo, Japan

Prof. Hao Yan
ASU, USA

Prof. Andy Pimentel
UvA, NL

Prof. John Boland
CRANN Dublin, ROI

Prof. Luis Ceze
UW, USA

Prof. Hui-Ming Chen
CAS, China

Prof. Roland Wiesendanger
Universität Hamburg
"Nanoscale Magnetic Knots – a New Twist for Spintronics"

Prof. Sang Lyul
SNU, South Korea

Prof. Ross D. King
University of Manchester, UK

2014

ESF Groups: Topic Workshop

Clusters' Meeting at DFG

2015

Grand Professor Week

Summer Symposium

Ground-breaking New Building

Summer School (DMA)

2016

Career & Grand Professor Week

cfaed Seminar Series

Public Outreach

The focus of cfaed's PR activities is to translate the scientific context of the Cluster in such a way that it becomes transparent, comprehensible, and accessible. Various audiences are targeted: the local, national, and international scientific community, the scientifically-interested public, journalists, politicians, and industry.

Scientists as PR agents

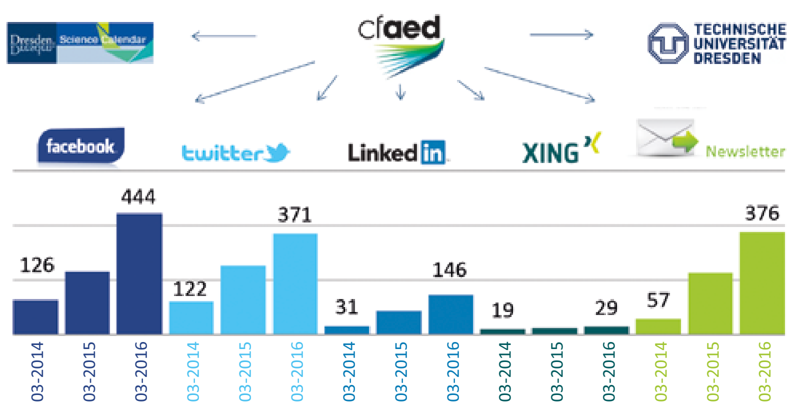
cfaed's scientists are the best PR agents! Their significant presence at international and national conferences and workshops, as well as their participation in events such as science slams or in scientific exchange programs, e.g., cfaed's INSPIRE Grants foster the Cluster's visibility in an incomparable manner.

Spreading the word

A range of activities helps to spread the latest news, scientific results, and general information on cfaed's research program. Besides the standard toolbox of media relations, lots of additional instruments and actions support cfaed growing into an internationally known research platform. Representations at international fairs and exhibitions strengthen the Cluster's visibility and support networking activities. A variety of printed publications were produced in-house, including brochures, flyers, posters, reports, and calendars.

Becoming visible

Regular public talks including the high-profile cfaed Distinguished Lecture Series, the participation in Dresden's renowned 'Long Night of Sciences' as well as guided lab tours promote the Cluster to a wide range of interested audiences. A vibrant homepage is the foundation for the manifold activities in the online world and a purpose-built database provides an up-to-date overview about all publications by cfaed groups. Energetic social media channels and a public newsletter broaden the range of people that can be reached.



Growth of 1st-grade followers on selected online communication channels. The columns show the development of the years 2014-2016 for each channel.

International Fairs & Exhibitions

During the past three years, cfaed was not only represented at numerous international fairs and exhibitions but also, many conferences and workshop have been attracted to Dresden by cfaed investigators. Such activities help to promote the Cluster within the research community and display the latest research results. The following overview is a selection of conferences.

2013

1st Dresden Nanoanalysis Symposium
Dresden – 04/2013

Vehicular Technology Conference, VTC2013-Spring
Dresden – 06/2013

Semicon Europa
Dresden – 10/2013

2014

Design, Automation and Test in Europe, DATE'14
Dresden – 03/2014

Deutsche Physikalische Gesellschaft (DPG), Spring Conference
Dresden – 04/2014

Hannover Messe
Hannover – 04/2014

DNATec Conference and Exhibition
Dresden – 05/2014

TechConnect World Innovation
Washington, D.C. – 06/2014

Nanofair
Dresden – 07/2014

2nd Dresden Nanoanalysis Symposium
Dresden – 07/2014

Silicon Saxony Day
Dresden – 07/2014

Semicon Europa
Grenoble – 10/2014

2015

Novel High k Applications Workshop
Dresden – 03/2015

CeBIT
Hannover – 03/2015

Frontiers of Characterization and Metrology for Nanoelectronics
Dresden – 04/2015

3rd Dresden Nanoanalysis Symposium
Dresden – 04/2015

Hannover Messe
Hannover – 04/2015

German THz Conference
Dresden – 06/2015

Nano-scale Materials – Characterization-Techniques and Applications
Dresden – 06/2015

Plasmonics for Nanostructure Characterisation
Chemnitz – 06/2015

European Polymer Congress
Dresden – 06/2015

Nanoscale Assemblies of Semiconductor Nanocrystals, Metal Nanoparticles and Single Molecules: Theory, Experiment and Application
Dresden – 08/2015

Functional Polymer Materials for Electronics, Energy Technology and Medicine
Dresden – 08/2015

Engineering Life
Dresden – 09/2015

Semicon Europa
Dresden – 10/2015

2016

Design, Automation and Test in Europe, DATE'16
Dresden – 03/2016

Modeling of Systems and Parameter Extraction Working Group
Dresden – 03/2016

CeBIT
Hannover – 03/2016

4th Dresden Nanoanalysis Symposium
Dresden – 06/2016

20th European Symposium on Polymer Spectroscopy
Dresden – 09/2016

Participating Institutions

Technische Universität Dresden – Host University

TU Dresden – one of eleven German "Excellence Universities" – is the largest university in Saxony with about 37.000 students and nearly 8.000 staff members – among them over 500 professors.

TU Dresden succeeded in the German Excellence Initiative in all funding lines including: the institutional strategy 'The Synergetic University', two Clusters of Excellence 'Center for Advancing Electronics Dresden' (cfaed) and the 'Center for Regenerative Therapies Dresden' (CRTD), as well as the 'Dresden International Graduate School for Biomedicine and Bioengineering' (DIGS-BB).

In 2009, TU Dresden initiated an association of research and cultural institutions called DRESDEN-concept (Dresden Research and Education Synergies for the Development of Excellence and Novelty), which today includes 22 institutions and which is unique in Germany.

Technische Universität Chemnitz – Cooperating University

TU Chemnitz hosts about 11.000 students and nearly 180 professors. The research focuses on the key areas 'Energy-efficient Production Processes', 'Smart Systems and Materials', and 'Human Factors in Technology', which are closely interacting across eight faculties.

Helmholtz-Zentrum Dresden-Rossendorf

HZDR works on research projects ranging from discovering basic principles in the natural sciences to generating ideas for new products and innovations. New materials are investigated in order to better understand, optimize, and use them for specific applications. This includes novel super- and semiconducting materials using very high magnetic fields or ion beams.

Leibniz Institute of Polymer Research Dresden e.V.

The combination of competences in natural and engineering sciences as well as state-of-the-art technical equipment at the Leibniz IPF allows a holistic approach to material science research. In this way, it is possible to deal with problems of and requirements on new and improved polymer materials, preparing their transformation into an industrially utilized product.

Leibniz Institute for Solid State & Materials Research Dresden

The Leibniz IFW focuses on functional materials which hold a key position in many fields of application: superconducting and magnetic materials, thin film systems and nanostructures as well as crystalline and amorphous materials. The Institute's mission includes fundamental and applied research and development with emphasis on solid state and materials research.

Max Planck Institute of Molecular Cell Biology and Genetics

"How do cells form tissues?" still is the question that researchers at MPI-CBG are tackling from different angles. Molecular cell biologists provide insight into basic processes of cellular life and organization. The research in the institute encompasses many topics from molecular, cellular, and developmental biology as well as from biophysics.

Max Planck Institute for the Physics of Complex Systems

The organizational concept of the MPI-PKS rests on two pillars: in-house research and a visiting scientists program. The research ranges from classical to quantum physics and focuses on three main areas, which correspond to the activities in the three divisions: Condensed Matter; Finite Systems; Biological Physics.

Fraunhofer Institute for Ceramic Technologies

The Fraunhofer IKTS conducts applied research on high-performance ceramics. In materials know-how, production technologies, and system/product integration, chemists, physicists, and materials scientists are supported by experienced research engineers and technicians in activities focused on structural and functional ceramics technology platforms.

Fraunhofer Institute for Electronic Nano Systems

The Fraunhofer ENAS in Chemnitz focuses on the field of smart systems integration by using micro and nano technologies. It offers research and development as well as services in: Smart Systems Integration; Micro and Nano Systems; Reliability; Printed Functionalities; Back-End of Line for microelectronics and nanoelectronics; and 3D integration.

Nanoelectronic Materials Laboratory gGmbH

NaMLab is a TU Dresden company. Based on key expertise in dielectric materials for semiconductor devices, NaMLab focuses on the integration and application of its materials competence applied to reconfigurable and energy efficiency devices by placing the device rather than the material system itself into the center of its research activities.

Kurt-Schwabe-Institute for Measuring and Sensor Technology Meinsberg e.V.

The institute with its distinguished competence concerning measuring and sensor technology aims to do basic, but practical-oriented research in the fields of physical and electrical chemistry, sensor technology, materials science, and science orchestration.

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