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Progress in Physics (108)

Atomic-Scale Electronics and Photonics for Sustainable AI Technologies and Beyond

Miklós Csontos ^{1*}, Alexandros Emboras ^{2*}, Mathieu Luisier ², and Juerg Leuthold ¹

¹ Institute of Electromagnetic Fields (IEF), ETH Zurich, CH-8092 Zurich

² Integrated Systems Laboratory (ISL), ETH Zurich, CH-8092 Zurich

* Corresponding Authors: csontos@ethz.ch, emborasa@ethz.ch

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Introduction

Artificial intelligence (AI) is shaping modern societies at unprecedented scales – and pace. State-of-the-art semiconductor technologies increasingly struggle to keep up with their seven decade long thrive and can thus only provide temporary solutions to the AI-generated global-scale computational challenges. The latter are dominated by exponentially growing data generation, traffic, and processing needs arising from generative AI platforms, crypto-currencies, and the Internet-of-Things (IoT), a world-wide network of autonomous systems interconnected via the Web, to name a few examples. The major persisting computational – and ecological – bottlenecks of AI come (i) from the currently prevailing von Neumann architecture of the underlying hardware where memory, storage, and information processing rely on physically separated units, which necessitates permanent, extremely energy-hungry data shuttles, and (ii) from the exploding training overheads of generative tools, e.g., large language models (LLM). As a result, the global energy demand of computation is foreseen to approach the total production of our planet – within a decade [MEHONIC2022]. This trend is not sustainable: Alternative AI solutions are therefore imperatively and instantly needed.

The computing approaches of the human brain provide important insights and clear pathways to address these challenges through adaptive, multifunctional units (our neurons and synapses), the seamless collocation of information processing and storage, low-energy operation, and adaptive learning rules [ZIDAN2018]. Memristors [STRUKOV2008], which are atomic- to nanometer-scale devices, can emulate the aforementioned biological features through modulations of their electrical conductance at competitively low energy costs and versatile time scales. Thus, they can act in artificial neural networks (ANNs) both as multifunctional synapses [WEILENMANN2024] and neurons [KUMAR2022], as illustrated in Figure 1. Moreover, they can be arranged into high-density and fully interconnected matrix-like structures, called crossbar arrays [XIA2019], and monolithically integrated with existing semiconductor platforms [CAI2019]. Such architectures can implement simplistic and powerful learning rules, inspired by the functionality of the human brain, and demanding arithmetic operations even in single time-steps due to their physical characteristics and interconnectivity.

In this paper we provide insight into our ongoing work that has explored the physical boundaries of memristor operation in the space, time, and energy domains. Our studies have revealed the ultimate, single-atom scaling limit [CHENG2019], multilevel conductance tunability [PORTNER2021], and ultra-fast switching [CSONTOS2023] of these

devices. Operation down to the femtojoule energy level has been demonstrated, outperforming the energy-efficiency of individual neurons in the human brain [SCHMID2024]. Accordingly, in our latest works we showed that several key functions of modern AI algorithms can be emulated using a single nanometer-scale device operated at the lowest possible power [LEWERENZ2024, PORTNER2024, WEILENMANN2024]. Beyond the above breakthroughs implemented in the electronic domain, the functionalities of our single devices have been vastly extended by the chip-scale integration of electronic and photonic degrees of freedom [EMBORAS2018]. These achievements are key enablers for next-generation brain-inspired computational and communication platforms, where low-energy operation is granted by memory/processing collocation, adaptability, increased functional complexity and reduced time-complexity from the single device- to the system-level.

Memristor: a versatile alternative to the CMOS transistor

Memristors are two-terminal solid-state devices exhibiting tunable conductance. The device layout typically consists

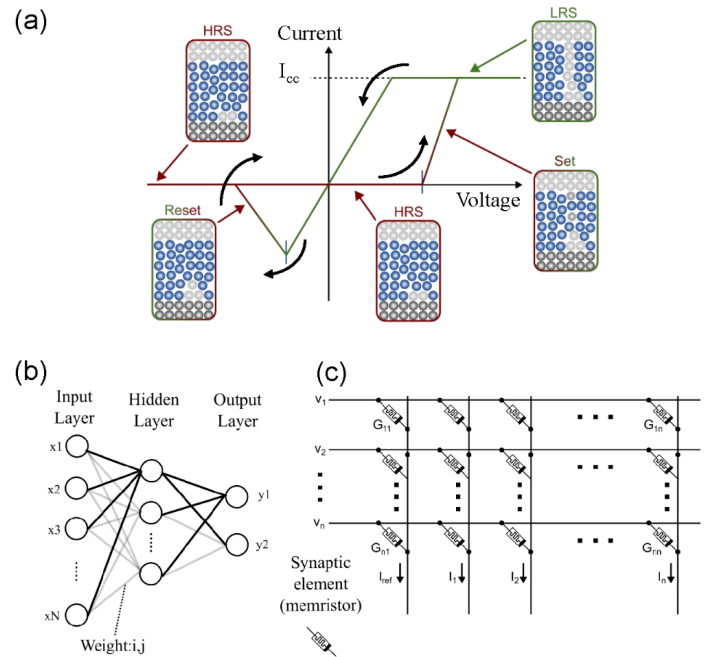


Figure 1: Operation cycle of a non-volatile filamentary memristor and its application in the synaptic layers of artificial neural networks (ANN). (a) Typical hysteretic current-voltage characteristics and the associated structural changes in the metal (grey) – insulator (blue) – metal (grey) structure. (b) Schematics of an ANN. The circles (solid lines) represent neurons (synaptic weights). (c) Illustration of a memristor crossbar array implementing a fully connected synaptic layer. Memristors sit at each cross point.

of two metallic electrodes terminating an insulating layer, as shown in Figure 1a. Under the influence of external electrical, thermal, or optical stimuli, various electrochemical processes may take place in the insulator, such as oxidation/reduction reactions and ionic/atomic transport. These often result in the formation of nanoscale conducting regions, so-called filaments, capable of bridging the metallic terminals through the insulating layer. The atoms contributing to the conducting filament may be sourced from an active electrode, such as Ag or Cu (electrochemical metallization - ECM) or, alternatively, from the generation of oxygen vacancies at metal-oxide interfaces (valence change mechanism - VCM) [WASER2009]. As will be discussed in the following, the controllability and scalability of such conducting filaments down to the ultimate, single-atom level play a fundamental role also in low-energy and high dynamic range memristor operation.

While the operation of memristors based on atomic- to nanometer-scale conducting filaments depends on ionic rearrangements, that of conventional complementary metal-oxide-semiconductor (CMOS) transistors relies on the formation of an electronic conducting channel at their metal-oxide interface. In particular, memristors exhibit more conductance (resistance) states for computation and data storage than transistors, extending over a >10 orders of magnitude wide window. These key features are enabled by their unique conduction phenomena, which range from (i) electron tunneling through (ii) the contribution of individual atomic orbitals of a single-atom junction, (iii) discrete conductance steps arising from the atom-by-atom growth of oxide layers to (iv) diffusive conductance in nanometer-scale disordered conductors. Among them, the ultimately available resistance states can be conveniently tailored to the desired application by materials engineering.

Furthermore, conducting channels created by the rearrangement of ions/atoms rather than by electronic effects, as in CMOS technologies, offer major competitive benefits: (i) The ultimate down-scalability to single-atom channel widths is enabled without a need for top-shelf lithographic facilities; (ii) information stored in atomic positions can be inherently robust, as opposed to electronic charges which are always prone to leakage due to quantum mechanical tunneling; thereby (iii) nonvolatile operation, i.e., safely preserving the stored information after disconnecting the power, also becomes possible. Meanwhile, the array-level scalability and CMOS compatibility of the prevailing memristive material systems also allow for the seamless integration of this emerging technology with state-of-the-art digital platforms.

Atomic-scale memristors: scalability, speed, and energy-efficiency

The resistance state of filamentary memristors can be tuned by relocating only a few atoms at interatomic distances in the active region of the conducting filament. Hence, it is conceivable that this relocation may occur at very short time-scales and at low energy cost. Thereby, the technology holds great promises also in view of high-frequency applications, such as those in the telecommunication domain, where the ever-increasing power consumption is a growing concern.

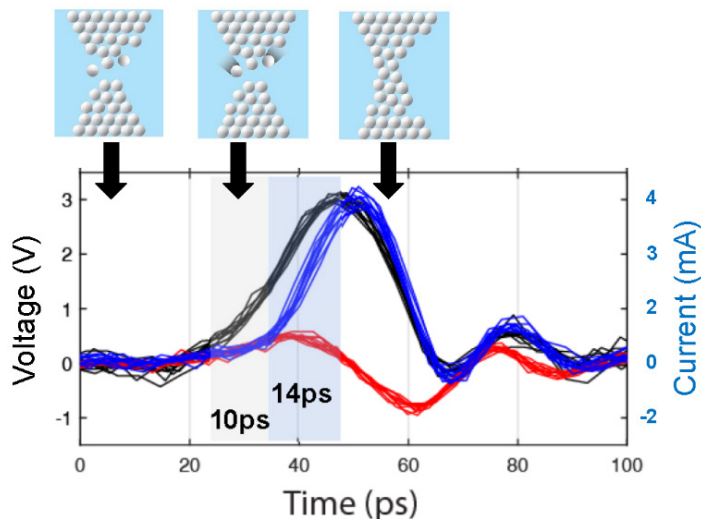


Figure 2: High-speed resistive switching experiment in a filamentary switching Pt/Ta₂O₅/Ta memristor. As illustrated by the schematics on the top, the atomic-scale filament is initialized in a disconnected, high-resistance state. When the voltage (black) is first applied, the current (blue) only exhibits a low-magnitude capacitive response (red), corresponding to the capacitance of the metal/insulator/metal structure. The onset of the resistive switching transition follows the rise of the voltage pulse within 10 ps and completes in another 14 ps. During the falling edge of the voltage pulse, a current proportional to the voltage is observed, which is a hallmark of an Ohmic link.

In this context, we demonstrated unprecedented resistive switching speeds in memristors incorporating a Ta₂O₅ oxide layer deposited between Pt and Ta electrodes. These devices were operated in the single- to few atom switching configurations, as revealed by the detailed analysis of the current-voltage characteristics [TÖRÖK2023]. An optimized sample design facilitating low parasitic capacitances enabled us to monitor the dynamics of the resistive switching during ultra-short programming voltage pulses. As a result, filament formation times down to the 10 ps time-scale could be measured at picosecond resolution, as explained in Figure 2. Moreover, the dynamics of the slower, thermally activated processes governing the dissolution of the conductive filament upon a reversed bias voltage polarity was also characterized. Thus, the electric-field-induced and diffusion-driven resistive switching mechanisms could be experimentally sorted, which is a prerequisite for the optimization of high-speed cyclic memristor operation [CSONTOS2023].

To determine the energy cost of the resistive switching, the bias voltage, the resulting device current, and the duration of the switching operation must be taken into account. As the key figure of merit of filamentary resistive switching dynamics – which spans from picoseconds to years in the time domain – the completion of a filamentary bridge requires an exponentially shortened time as the bias voltage is linearly increased, which follows from the activated nature of ionic transport through solid dielectrics. As a result, faster resistive switching operation is energetically more favorable even at the expense of an increased applied bias voltage. This is in contrast with the switching dynamics of CMOS transistors, where a simplistic plate capacitor model predicts a gate-voltage-independent switching energy. Accordingly, our recent nanosecond to picosecond time-scale experiments revealed resistive switching energies in the 1 to 100 fJ regime, surpassing the energy-efficiency of neurons in the human brain [SCHMID2024].

Memristors as artificial synapses and neurons

Thanks to customizable, volatile or non-volatile memory effects arising from the short- and long-term stability of their conducting filaments, memristors can act both as solid-state neurons or synapses, as illustrated in Figure 3. When used as artificial synapses, the strength of the synaptic connection is represented by the device conductance which can be incrementally tuned by successive positive or negative voltage pulses. The permanent nature of such conductance changes facilitates in-memory computing, where the co-localization of the computing and memory functionalities inherently eliminates the aforementioned von Neumann bottleneck. In contrast, memristors used as artificial neuron circuits exploit volatile memory effects: Upon receiving a critical amount of input stimuli, they respond with a short-term, temporary conductance change. By embedding a volatile memristor into a simplistic electronic circuit environment, the transient effect of the latter can be harnessed to implement the (leaky) “integrate and fire” operation of biological neurons at a competitively low footprint and energy consumption [LEWERENZ2024].

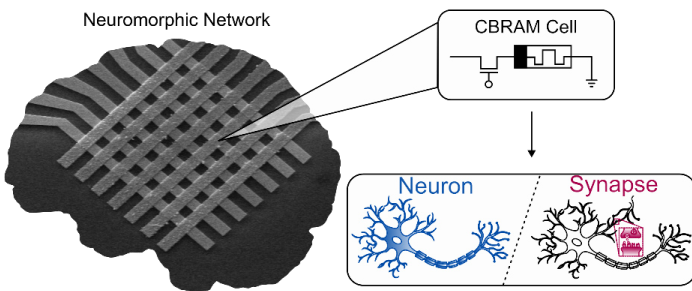


Figure 3: Illustration of a neuromorphic network consisting of memristors, a.k.a. CBRAM cells, which can be configured to emulate either neuron or synaptic functionalities [PASSERINI2025].

Over the last 8 to 10 years, our objective has been to establish a versatile platform where, depending on the actual application, individual devices in high-density memristor arrays can be conveniently and reproducibly reconfigured between such synaptic or neural operation. To achieve this goal, a better control over the formation and stability of the conducting filament is necessary. We found that by alloying the widely applied Ag electrodes with other metallic compounds, such as Sn, a more complex but also more customizable conducting filament structure can be created in SiO_2 dielectric layers. In agreement with molecular dynamics calculations and scanning electron microscopy studies, at low concentrations the less mobile Sn atoms form a stable ‘backbone’ across SiO_2 , where the originally more mobile Ag atoms can anchor. Depending on the current level at which the conductive filament is formed, different Ag/Sn ratios can be achieved in the filamentary region, resulting in its (de)stabilization at zero voltage bias, favoring (neuronal) synaptic operation [PASSERINI2023].

A neuromorphic application of atomic memristors: solving navigation tasks

Autonomous systems – smart devices which can make decisions and act without human involvement – are at the center of the ongoing fourth industrial revolution. Among them, the development of systems capable of navigating complex environments has been transforming major industries such as automotive, aviation, health care, or defense. Current state-of-the-art autonomous navigation platforms rely on billions of CMOS transistors and traditional machine learning algorithms. They are extremely power demanding – and also prone to frequent, potentially hazardous failure. This is in contrast, for example, to the abilities of the honey bee, which performs sophisticated navigation tasks and exhibits social behavior with only one million neurons in its brain.

We recently showed experimentally that the combination of dedicated atomic memristors with cutting-edge neuroscience theories allows for similarly efficient navigation and search operations in hardware [PORTNER2024]. Particularly, our framework takes advantage of a bio-inspired, three factor learning rule, where the added third factor emulates the functionality of biological dopamine and acts as a reward signal. Such learning rule was implemented on our tunable, analog, and multifunctional atomic memristors rather than by combining CMOS transistors and demanding machine learning algorithms [PORTNER2024]. Using this framework, we demonstrated how a mouse learns the optimal trajectory through a simple, T-like maze environment, to find a reward in the form of a piece of cheese, as shown in Figure 4.

Photonic memristors

While neuromorphic systems offer high speed and low power consumption, reaching the capabilities of the human brain requires connecting millions, if not billions, of individ-

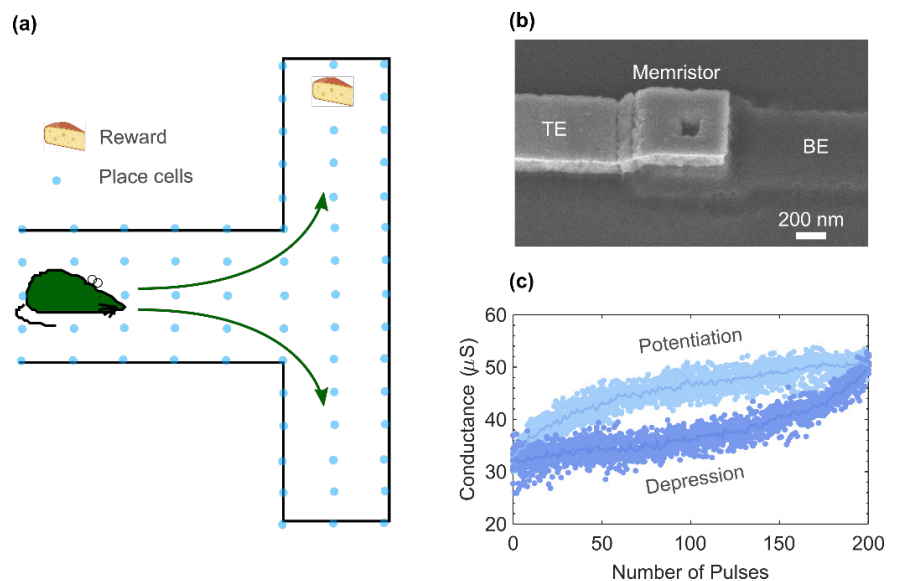


Figure 4: Memristor-based implementation of a navigation task. (a) Schematic of a reward-based learning experiment: A mouse learns how to go through the desired sequence of actions (moving forward, turning left) to reach a designated location where a reward, a piece of cheese, is deposited. At each discretization point, the animal chooses the action (moving East, West, North, South, or Stop) that eventually brings it to the reward (piece of cheese). This experiment was implemented on hardware (b) and in-software emulated memristors whose conductance can be gradually modulated between a high and low resistance state upon the application of voltage pulses. The corresponding potentiation and depression measurements of these devices are shown in (c).

ual memristive devices, leading to significant energy losses and performance bottlenecks. Optical communication links present a promising alternative to electrical interconnects, combining fast data transmission with minimal energy use.

An optical communication link typically comprises lasers, modulators, and photodetectors, and can be implemented based on various material systems. Silicon photonics platforms have established themselves as the state-of-the-art for applications requiring high bandwidths of few 10's of GHz [ASSEFA2012], while plasmonic-organic platforms have achieved speeds of more than 500 GHz [BURLA2019]. Yet, their basic building blocks (modulators, photodetectors, and lasers) are bulky compared to the size of electronic components. This is where memristors come into play: When combined with optical signals, they provide an attractive alternative to standard technologies. Indeed, optical memristive effects have recently pushed device miniaturization well beyond previous limits. We advanced this vision by embedding a CBRAM-type memristor into a plasmonic/photonic circuit, and demonstrated that it can serve simultaneously as a modulator, photodetector, and laser source [EMBORAS2016, EMBORAS2018, CHENG2022].

Back in 2016, we reported the first memristive plasmonic modulator operating on the atomic scale [EMBORAS2016]. The device structure and functionality are shown in Figure 5a. A silicon waveguide channels an infra-red (IR) light beam into a narrow slot where it is covered by an insulating layer of amorphous Si (a-Si) that fills the gap between two metal electrodes, silver and platinum. The Ag–a-Si–Pt stack forms a CBRAM cell. The slot converts the incoming optical beam into a surface plasmon (carrier oscillations) that can, under the right conditions, squeeze through the tiniest part of the gap and reach the opposite side of the structure, where it is converted back to a photon beam. The optical transmission of the fabricated device is controlled by a voltage applied to the CBRAM, upon which an Ag filament grows and dissolves between the Ag and Pt electrodes. Depending on whether this filament short circuits the metallic plates or not, IR transmission is turned off or on, respectively. The binary switching mechanism between these two states and the resulting optical transmission therefore rely on the electrically-controlled relocation of a few atoms (≤ 20), which change the resonance frequency of the plasmonic cavity.

A memristive photodetector based on light-induced relocations of atoms was fabricated as next step [EMBORAS2018]. It is illustrated in Figure 5b. The realized structure consists of a silicon photonic waveguide butt coupled to a vertical 3-D atomic point contact of Ag-SiO₂-Pt material stack. In this

combined experimental-theoretical work, we emphasized how a localized optical hot spot can efficiently interact with only a few atoms in a CBRAM cell through photonic/plasmonic couplers and thus modify its fundamental principles of operation, i.e., the current passing through the device.

To complete the photonic toolbox, a memristive, on-chip photon source, as visualized in Figure 5c, was developed [CHENG2022]. Such light sources offer a compact footprint, low power consumption, are operated electrically, and are compatible with standard CMOS fabrication processes. They thus enable high integration densities and energy-efficient operation at reduced cost. Our atomic scale memristive devices emit photons during resistive switching. Light emission occurs within the gap of an Ag/a-SiO_x/Pt junction under an applied voltage thanks to the special shape of the electrodes, engineered to form a plasmonic nanoantenna. Our demonstrations triggered a new conceptual paradigm of atomic scale devices combining electrical and optical functionalities within the same nanoscale unit. Thereby, we successfully addressed the challenge of downscaling photon sources, photodetectors, and electro-optical modulators to dimensions comparable to those of electronic components.

Embedding memristive modulators, photodetectors and photon sources directly into neuromorphic hardware could pave the way for high-speed photonic inter-chip links. Furthermore, the light-driven memory effects intrinsic to memristors can be exploited to tune solid-state synapses more precisely and to endow them with additional capabilities—namely, computation and data storage carried out entirely in the optical domain [EMBORAS2020].

Outlook

After developing a versatile memristive toolbox, the next phase of our research is dedicated to system level integration and promoting these technologies in application areas where their utilization has only become possible due to our latest breakthroughs. The integration efforts aim at the design and fabrication of combined CMOS and memristor arrays where memristor-based synapse and neuron arrays can emulate various machine learning tasks, alleviating some of the most demanding software overheads of typical AI tasks. Potential new application areas are mounting in the field of optical communication, where the highest operation speeds, electronic – photonic conversion, as well as low footprint, energy consumption and latency are key requirements.

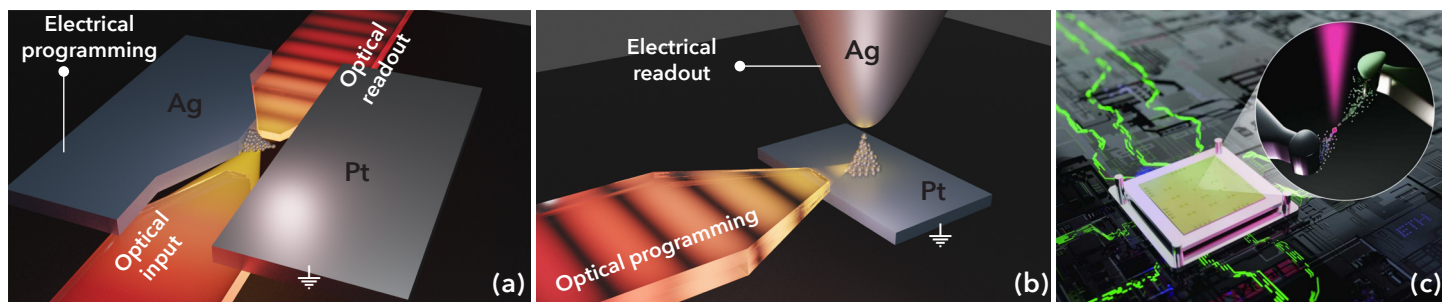


Figure 5: Photonic memristive platform. (a) Electro-optical modulator [EMBORAS2016]. (b) Photodetector [EMBORAS2018]. (c) Photon source [CHENG2022]. Sub-plots (a) and (b) reprinted from [EMBORAS2020] with the permission of AIP Publishing.

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Miklós Csontos received his diploma in engineering physics and PhD in physics at the Budapest University of Technology and Economics in 2002 and 2007. As a researcher at ETH Zurich, he focuses on the dynamical properties of resistive switching memories and their applications in neuromorphic computing.

Alexandros Emboras is Privat Dozent in the Department of Information Technology and Electrical Engineering of ETH Zurich. His research interests include photonics, plasmonics, and neuromorphic technologies. He earned his Ph.D. from CEA-LETI in France and his Habilitation from ETH Zurich in Switzerland.

Mathieu Luisier is Full Professor of Computational Nanoelectronics at ETH Zurich, where he also studied electrical engineering and did his PhD. He joined the faculty of ETH Zurich in 2011. Prof. Luisier received an ERC Starting Grant (2013) and an SNSF Advanced Grant (2022) to support his research.

Juerg Leuthold is the head of the Institute of Electromagnetic Fields of ETH Zurich. He was formerly affiliated with the Karlsruhe Institute of Technology. Prof. Leuthold is an Optica and IEEE fellow, and a member of the Swiss Academy of Engineering Sciences and of the Heidelberg Academy of Sciences.