MEMORY

MATERIALS

MEMORY MATERIALS

TOWARDS LOW-ENERGY COMPUTING

FELIX DESCHLER

We have come a long way since the early days of computing, when a hard disk weighed a ton and could store a fraction of the information a modern smartphone can hold. Since then, on-going advances in materials science have given rise to new kinds of memory devices. In a departure from traditional transistor-based technologies, researchers at the Institute for Physical Chemistry are seeking to design and investigate novel materials that exceed conventional semiconductor performance and reduce the amount of energy required both for storing and processing information. One approach is based on solution-processable materials that respond to light. Being able to read and access information by all-optical means would simplify the design of memory devices and could, in future, play a crucial role in reducing the substantial amounts of energy required to meet our computing needs.

The ability to store, access and process information is central to our everyday lives and is driving progress in societies. Passing on information across time and space and keeping records of past events has been crucial for initiating the rapid advances and progress that shape our modern world. In this article, we will be discussing how materials were, and are, at the heart of these developments. From the earliest use of inks to drawing pictures on stone to writing texts on paper, the clever use of materials has always been a key part of information technologies.

Evolving memory materials

A dramatic advance in our ability to store information occurred in the last century when electronic and magnetic devices were discovered which could store information on ever smaller volumes. The invention of the transistor by Shockley, Brattain and Bardeen allowed information to be memorized and read electronically, which opened up a new field of information technologies. Typical materials that were used in the first years were semiconductors such as silicon or mixtures of elements from the third and fifth column in the periodic system. The key material advance that enabled the design of high-performance transistor technologies was the fabrication of semiconductors in monocrystalline form and with very high elemental purity. Today, these semiconductor materials can be made with the exceptional precision of less than one impurity atom per square centimeter. With this advance, there are now memory devices that can rapidly store and read information, and the use of transistors is still key to how most computers operate today.

The second advance in memory materials in the last century was long-term information storage based on magnetic materials. Here, information was stored as the magnetization state of magnetic materials. A main technical advance in this context was the ability to control the magnetization state of magnetic materials down to the length scale of a few nanometers. Initially, iron-oxide was used as magnetic storage material, whereas now cobalt-based alloys are often used. The main challenge for these materials was achieving high magnetic quality for retaining the magnetization state over long periods of time during long-time storage, while still keeping the energies used for switching events low. To achieve this, it proved crucial once again to produce these materials with high purity and defined magnetization orientation. Large improvements in write/read speeds and information density were achieved by nanoscale fabrication and novel concepts for controlling the magnetic interactions between the read/write head and the storage material. While the first hard disk in 1956 weighed a ton and could store up to five million characters, a modern smartphone can store up to one trillion characters. To put this in context: this article contains about 17,000 characters. Thus, materials have been instrumental in increasing our ability to store, transfer and access data in our lives over the last decades.

Next-generation information storage

On the magnetic materials side, the term "memory materials" now often refers to the use of antiferromagnets. These materials are expected to potentially replace ferromagnetic storage materials, since they show less external stray fields which can lead to loss of the magnetization state and thus loss of the stored information. However, because of this manipulating their magnetization state with external magnetic fields is more challenging than in usual ferromagnetic systems, where simply applying external magnetic fields with suitable orientation will switch the magnetization state of the memory material. A potential approach to address this issue is the use of electromagnetic fields in the terahertz range, which can be used to switch between different spin-ordering patterns of antiferromagnets. Another approach is the use of all-optical means in the visible and infrared region, which is at a higher frequency range than the terahertz regime, to write the memory state of materials. In this way, up to a thousand times higher switching rates for information bits could be realized, compared to electronic manipulation. However, such approaches require materials that combine magnetic and semiconducting properties, so that they can be addressed by photoexcitation. Other potential approaches include the use of magnetic organic molecules with stabilized radical spins, memristive electronic-ionic materials that change their electrical resistance under illumination, or optically active dilute magnetic semiconductors.

Solution-based semiconductors

Going towards next-generation information storage, one research direction of our "Functional Material Dynamics" group at the Institute for Physical Chemistry is the design and investigation of novel dilute magnetic semiconductors, in which we aim to use light to control the magnetization state. Such dilute magnetic-semiconductors, in which small amounts of magnetic elements are distributed in the crystal structure of a semiconductor, combine

magnetic and semiconducting properties. Previously, these materials were produced by elaborate co-evaporation of semiconducting elements and magnetic elements, such as manganese or cobalt.

We are exploring a new approach to producing these materials, using solution-processable materials known as hybrid metal-halide perovskites. These materials consist of metal elements combined with organic molecule components that self-assemble into crystalline structures. A special advantage of the perovskites is that they are relatively easy to fabricate from solution at low temperatures. While materials that are assembled from solution are often disordered and amorphous, the hybrid perovskites form polycrystalline films with unexpectedly high order and crystal purity. Furthermore, there is an unexpectedly low impact of defects, which can never be fully avoided in solution-based processing, on the optoelectronic performance of these materials. Several key material applications have since been reported, such as lasing and efficient light-emitting diodes, highlighting the perovskites' excellent properties and potential for use in optoelectronic applications. The hybrid nature of these perovskites also gives them a soft material structure, which leads to unusually strong responses of the atomic positions to photoexcitation. To investigate these excitation processes, we have studied the hybrid perovskites with state-of-the-art ultrafast X-ray diffraction experiments at national free-electron laser facilities, such as the European X-ray Free Electron Laser (EuXFEL) in Hamburg.

Designing novel memory materials

Perched as they are at the interface between established inorganic crystalline semiconductors and molecular organic semiconductors, hybrid perovskites provide an exceptionally interesting field for scientific investigations into semiconductor physics and materials science. Currently, we are exploiting the unusual defect tolerance of hybrid perovskites for novel memory materials and concepts in opto-spintronics – a new branch of spintronics where light is used to study or control electron spin. During fabrication of classical semiconductors large efforts are undertaken, typically to avoid introducing defects, since even small densities lead to large decreases in semiconductor performance. Since the elements used for conventional semiconductors are not magnetic, the aim to introduce 'defect' atoms with magnetic properties, while keeping the excellent semiconductor performance required for applications, has turned out to be very challenging. The defect tolerance and solution-processable nature of hybrid perovskites allow for introducing magnetic dopant atoms by facile solution-based methods. Notably, we found that high densities of magnetic dopants can be incorporated into the hybrid perovskites without destroying their semiconducting performance, but rather exceeding the performance typically achieved by classical semiconductors.

The ultimate goal of our material design efforts would be the discovery of systems with (anti-)ferromagnetic properties that are also semiconductors. In these systems one would be able to read the magnetization state by all-optical means, which would simplify the design of memory devices. While magnetic

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ordering has remained elusive so far, we have discovered that the presence of magnetic dopants gives rise to several new effects, with potential for information storage. Since the perovskites maintained their very good performance as semiconductors, we studied how alignment of the magnetic elements affects their luminescence properties. We found that the alignment of magnetic dopants in an external magnetic field changes the polarization state of the luminescence, giving it the special property of circular polarization. This can be pictured as the electromagnetic field of the generated light propagating in a helix-like shape in space. Such light is of interest for several applications, such as displays, sensors and quantum technologies. In addition to their technical relevance, these materials also show intriguing novel physical mechanisms for which we are developing a fundamental understanding using ultrafast optical spectroscopic methods.

Beyond our interest in hybrid perovskites, we are also studying the dynamics of excited states in low-dimensional magnetic semiconductors, which consist of only a single layer of atoms. These materials can show exotic excited electronic states, which are only present due to the low-dimensional nature of the materials. Using our spectroscopic methods at low temperatures and in magnetic fields, we gain unique insights into the energy levels and dynamic processes of these states. An understanding of these key material properties is crucial for their translation into real-life devices.

Towards low-energy, light-based computing

The rapid progress in the technical abilities of memory applications comes at the cost of a rapidly increasing energy consumption. Accessing one bit of information

PROF. DR FELIX DESCHLER joined Heidelberg University as full professor in physical chemistry in 2022. His research group “Functional Material Dynamics” is based at the Institute for Physical Chemistry. He studied physics at the University of Bayreuth, followed by a doctorate at LMU Munich in the area of organic semiconductor spectroscopy. He then moved to the University of Cambridge (England) for a postdoctoral position, where he was awarded a Herchel Smith Postdoctoral Fellowship, followed by a Winton Advanced Research Fellowship for an independent group leader position. In 2019, Felix Deschler moved back to Germany to set up a DFG-funded Emmy Noether group at the Technical University of Munich. He was awarded an ERC Starting Grant in the same year.

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Institute for Molecular Systems Engineering and Advanced Materials

Am Institute for Molecular Systems Engineering and Advanced Materials (IMSEAM) an der neuen Ingenieurwissenschaftlichen Fakultät forschen Wissenschaftler:innen der Universität Heidelberg zu neuartigen Materialien und Technologien auf molekularer Ebene. Auf einer Fläche von rund 620 Quadratmetern sind in dem Gebäude für Molecular Systems Engineering, das im April 2023 seiner Bestimmung übergeben wurde, eng verzahnt chemische, physikalische, molekular- und zellbiologische Labore angesiedelt. Das mehrgeschossige Gebäude auf dem Campus Im Neuenheimer Feld schließt neben den Materialwissenschaften – der Forschungsbau für Advanced Materials wurde im Jahr 2017 eröffnet – auch an das im Herbst 2022 eingeweihte European Institute for Neuromorphic Computing (EINC) an.

Die interdisziplinäre Forschung in diesem Innovationsfeld bildet einen zentralen Baustein der Flagship-Initiative „Engineering Molecular Systems“, die im Rahmen der Exzellenzstrategie etabliert wurde, um die Translation von Forschungsergebnissen in die Medizin ebenso wie den Transfer in technisch-industrielle Anwendungen zu forcieren. Natürliche und synthetisch hergestellte Bausteine auf der Ebene von Molekülen werden zu Systemen „zusammengebaut“, um damit molekulare Maschinen und Technologien mit neuen Funktionalitäten und Anwendungsmöglichkeiten unter anderem in den Lebenswissenschaften zu schaffen.

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requires about one nanojoule of energy, so reading this article from memory costs about one megajoule of energy. This value may appear to be very low for a single document. On a global scale, however, huge amounts information are processed by humanity, with the information processing sector being responsible for five to ten percent of global energy consumption. This energy demand, which is expected to increase in the next decades, comes at a large cost for the climate, if all this energy is produced from fossil fuels. Research into novel concepts and materials for information technologies that address this challenge is growing, seeking to discover solutions for performing the crucial tasks of memorizing and processing information at lower energies, higher speeds, and with more sustainable materials. Recently, novel directions have emerged for memory materials that could reduce the amount of energy required for both information storage and computing.

In the search for novel solutions for low-energy computing, approaches based on the design of neuromorphic circuits are emerging, i.e. computing concepts that resemble the working principle of our brains. The main advantage of these systems is that no information is stored during the computing process, which reduces computing energy demand dramatically. Such circuits could be of interest as hardware for artificial learning. While in our brains and in many existing neuromorphic circuits the information is transferred as electricity, one can also envision designing such systems based on light.

Using our expertise in light-matter interactions and ultrafast spectroscopy, we are exploring how ultrashort light pulses and novel materials can be combined to design next-generation concepts in photonic computing. Here, the very short pulses generated by our laser systems, with a duration of a few tens of femtoseconds, are one advantage we foresee, since they could achieve computing speeds as fast as several terahertz for single-pulse computing. This is about 1,000 times faster than the gigahertz calculation speeds in electronic processors right now. One could also consider using the different

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AUF DEM WEG ZUM LOW-ENERGY COMPUTING

FELIX DESCHLER

Materialien spielen eine entscheidende Rolle bei der Speicherung und Verarbeitung von Informationen. Die Fähigkeit, ein Medium mit externen Mitteln zu manipulieren, etwa so wie man Tinte zum Einfärben von Papier verwenden würde, ist der Schlüssel zur langfristigen Informationsspeicherung. Heute werden Informationen in der Regel von Computern verarbeitet. Für eine lange Zeit standen Transistoren im Mittelpunkt der Datenverarbeitung, doch nun entstehen neue Konzepte. In diesem Beitrag geht es um die Veränderungen, die neuartige Materialien künftig im Hinblick auf die Speicherung von Informationen bewirken könnten. Im Mittelpunkt steht dabei auch die Frage, welche Rolle die Wechselwirkungen solcher „memory materials“ mit Licht spielen könnten. ●

PROF. DR. FELIX DESCHLER ist seit 2022 Professor für Physikalische Chemie an der Universität Heidelberg. Seine Forschungsgruppe „Functional Material Dynamics“ ist am Physikalisch-Chemischen Institut angesiedelt. Er studierte Physik an der Universität Bayreuth und wurde anschließend an der Ludwig-Maximilians-Universität München auf dem Gebiet der organischen Halbleiterspektroskopie promoviert. Als Postdoktorand wechselte er an die University of Cambridge (England), wo er ein Herchel-Smith-Postdoc-Stipendium erhielt, gefolgt von einem Winton Advanced Research Fellowship für eine unabhängige Gruppenleiterposition. 2019 kehrte Felix Deschler nach Deutschland zurück, um eine von der Deutschen Forschungsgemeinschaft geförderte Emmy Noether-Nachwuchsgruppe an der Technischen Universität München aufzubauen. Im selben Jahr erhielt er einen Starting Grant des Europäischen Forschungsrats (ERC).

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„Der geschickte Einsatz von Materialien war schon immer ein Schlüssel für die Entwicklung von Informationstechnologien.“

properties of light to run multiple separate calculations with a single laser pulse. This could be based, for example, on the polarization states of light, which would create multiple parallel computing channels to enhance computing power. The ultrashort nature of our light pulses also fundamentally requires them to cover many different wavelengths, based on the uncertainty principle, which states that there is a limit to the precision with which certain pairs of physical properties can be known at the same time. This could be of advantage for computing, since there are techniques to separate the individual colors in a laser pulse, similar to those for separating the different colors in a rainbow, and then run calculations in each color range.

Finally, there is also the phase of light. It describes the pattern of the highest light fields spatially or temporally and can be modulated at high frequencies. Letting multiple pulses interact in a material will result in a complex interplay of their properties, which can then represent complex computing processes. However, this requires the light pulses to propagate in materials which show strong light-matter interactions. In this active area of research, polycrystalline materials with light-induced phase changes, or arrays of nanocrystalline materials might, in future, give rise to computing arrays that show strong light-matter interactions with our ultrafast laser pulses, allowing us to realize new concepts towards low-energy sustainable computing. ●

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