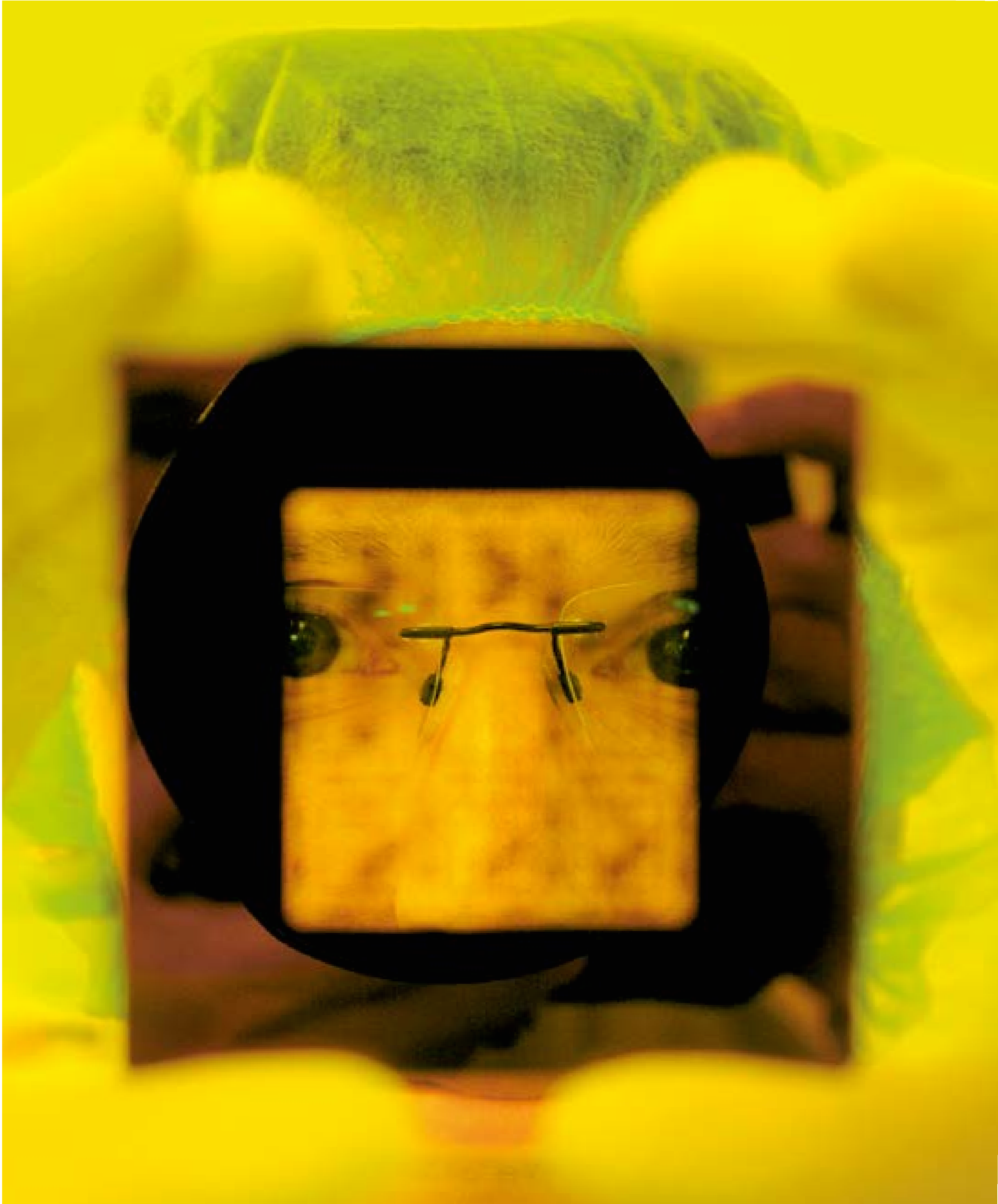

Irresistible **Logic**

Magnetic devices have long played an important role in memory systems but have not – yet – found a place in logic, the basic switching of ones and zeroes at the heart of digital computing and communications. Despite attractive characteristics such as ultra-low power consumption, magnetic logic has never been competitive with established, transistor-based technology. A case can now be made, however, for future chips incorporating both – thanks to novel nanomagnetic logic devices demonstrated at TUM's Chair of Technical Electronics.

Inspection of a mask used to apply metal contacts to nanomagnets: The mask is made of high-quality glass coated with 120 nm chromium that has been micro-structured by means of laser lithography.

Picture credits: Filser

3D-Anordnungen von Nanomagneten machen magnetische Computer attraktiv

In der Computertechnologie spielten magnetische Effekte bisher eine wichtige Rolle für Speicher. Im Hinblick auf logische Funktionen – dem allem digitalen Rechnen zugrundeliegenden Schalten zwischen Nullen und Einsen – konnte die Technik jedoch nie mit den auf Transistoren beruhenden integrierten Schaltungen konkurrieren. Mittlerweile steht der Industriestandard für digitale Computerchips, die CMOS-Technologie, vor grundlegenden Herausforderungen, denn die stetige Verkleinerung der Transistoren und die immer größere Packungsdichte der Schaltelemente auf einem Chip stoßen an Grenzen. Weltweit suchen Forscher nach völlig neuen Alternativen. Ein solcher Ansatz besteht im magnetischen Computer. Vielversprechende Experimente am TUM Lehrstuhl für Technische Elektronik zeigen auf, wie nanometergroße Magnete zu digitalen Logikgattern arrangiert werden können. Erzielt wurden diese Fortschritte im Rahmen einer langjährigen Zusammenarbeit mit der University of Notre Dame und dem TUM Lehrstuhl für Nanoelektronik. Der jüngste Durchbruch der Forscher war die Demonstration eines dreidimensionalen nanomagnetischen Logikgatters. Eine solche Struktur eröffnet die Möglichkeit, durch dreidimensional angeordnete Bausteine eine sehr hohe Packungsdichte auf der Chipoberfläche zu realisieren. Statt wie konventionelle Logik-Bausteine elektrische Ströme zu schalten, arbeiten die nanomagnetischen Strukturen durch Überlagerung magnetischer Felder. Einige ihrer Eigenschaften könnten für künftige Chips und Computersysteme hochattraktiv sein: Nanomagnetische Logikbausteine wären zum Beispiel nicht flüchtig, sie würden also ihre „1" oder „0" Zustände auch im ausgeschalteten Zustand behalten. Selbst im Betrieb würden nanomagnetische Schaltungen deutlich weniger Energie verbrauchen als vergleichbare Lösungen mit Transistoren. Außerdem könnten nanomagnetische Bausteine mit magnetischen Speichern integriert werden und so völlig neue Rechnerarchitekturen für Spezialanwendungen ermöglichen. Aus Sicht der TUM Forscher ist die Kompatibilität der nanomagnetischen Technologie mit CMOS besonders wichtig. Dadurch lassen sich zum einen gängige Produktionstechnologien einsetzen, um so ökonomisch von Skaleneffekten für die Massenproduktion zu profitieren, und zum anderen werden innovative Synergien zwischen den beiden Technologien möglich.

Patrick Regan (TUM)

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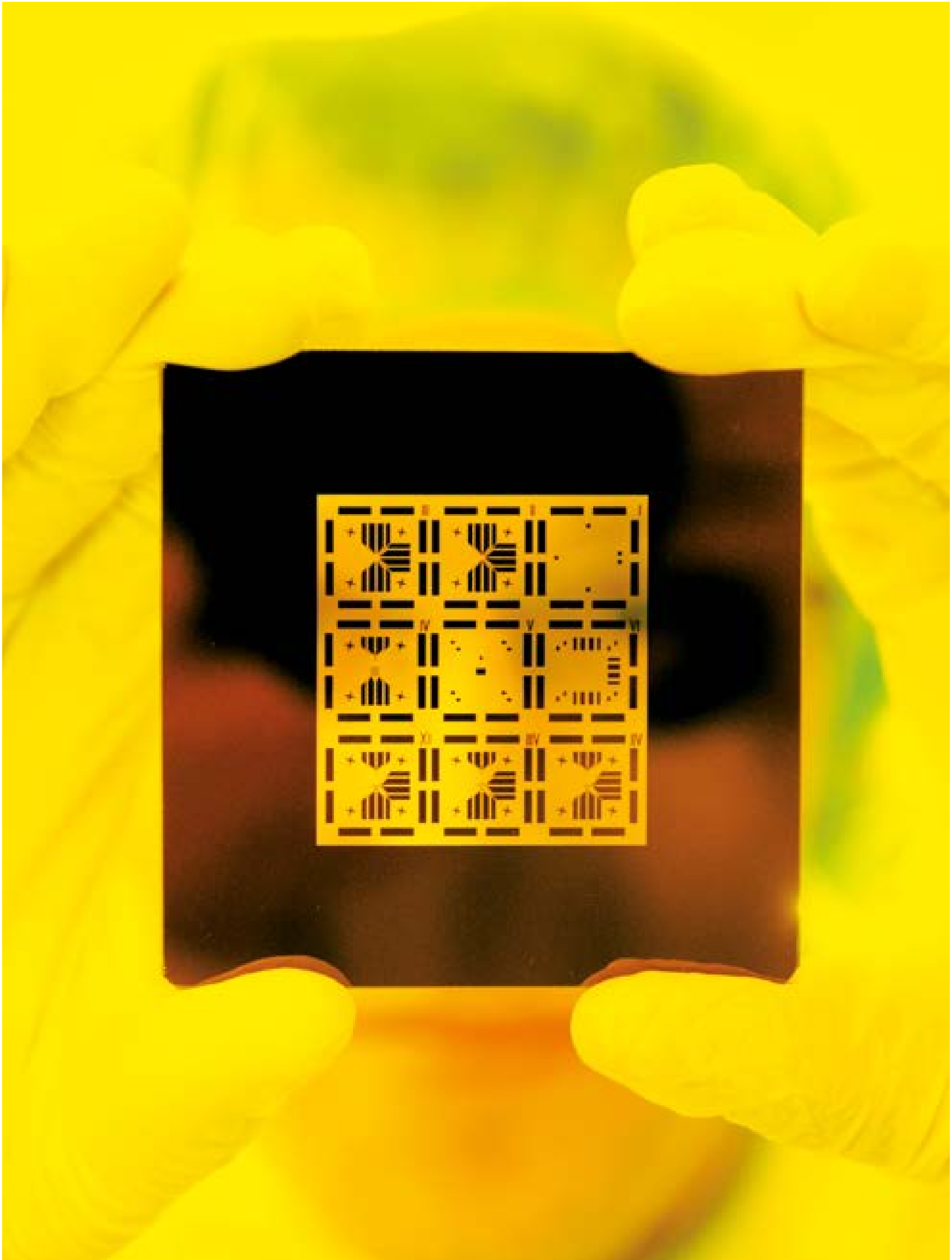
The transistor is one of the most basic building blocks of present-day civilization: This solid-state electronic gate switches the digital bits that define the information age. You can't see transistors any more, but they're everywhere you look. And in fact, they are everywhere you look largely because you can't see them. With features as small as a few tens of nanometers, transistors in the millions or even billions crowd the surface of integrated circuits – processors, memory components, controllers and single-chip realizations of whole systems. Beyond what they've done for computing, these chips, together with the intangible machinery of coding algorithms and software, have of course become the brains of the smart phone, the core of the car, part and parcel of everything from appliances to aircraft. This much of the story is widely known and fairly well understood.

What most denizens of today's information society do not appreciate and ideally need not know is that the stream of innovations they rely on flows from a hidden source: a crucible of marketplace competition, proprietary research and development, and precompetitive cooperation. It's the cooperative effort of drawing up and periodically revising a "roadmap" that has enabled the semiconductor industry, for decades now, to deliver steady, even predictable improvement in the capabilities and performance of integrated circuits while also bringing down costs.

A particular focus is on reducing the size of transistors, thus increasing their density on a silicon chip – especially within the technology system known as CMOS, or complementary metal oxide semiconductor. The workhorse of the industry, CMOS has performed like a racehorse in negotiating the famous "Moore's curve," which charts an aggressive path for processing power or memory at a given price. The expectation of endless progress, which the public takes for granted, rests on a vast amount of behind-the-scenes effort, cooperative as well as competitive. Obstacles are identified many years in advance, spurring the intensive research and development needed to stay on track.

"In applications such as parallel computing, data mining and pattern matching, nanomagnetic computing could have advantages over CMOS."
Markus Becherer

The obstacles now in sight may be the most challenging in the industry's history. Much progress to date has depended on scaling, with the development of ingenious ways to design and manufacture chips with ever smaller transistors. Make the transistor small enough, however, and quantum effects like tunneling come into play, exacerbating ▷

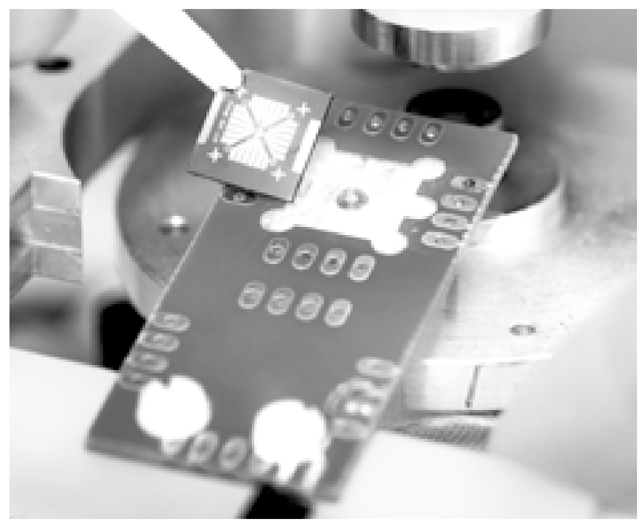


Picture credit: Filser

Picture credits: Filser

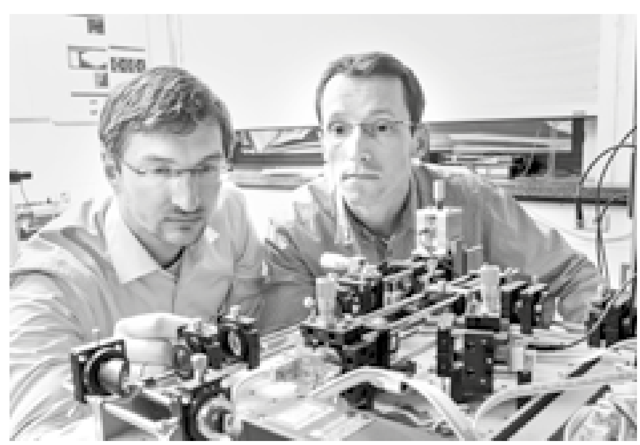
The nanomagnets are produced and characterized in the laboratory. Left: An electron beam evaporation system is used to deposit copper on the magnet sample's surface. The sample is placed above an electric coil (top right) to enable hysteresis measurements inside a magneto-optic Kerr microscope, which the scientists built themselves (bottom right).

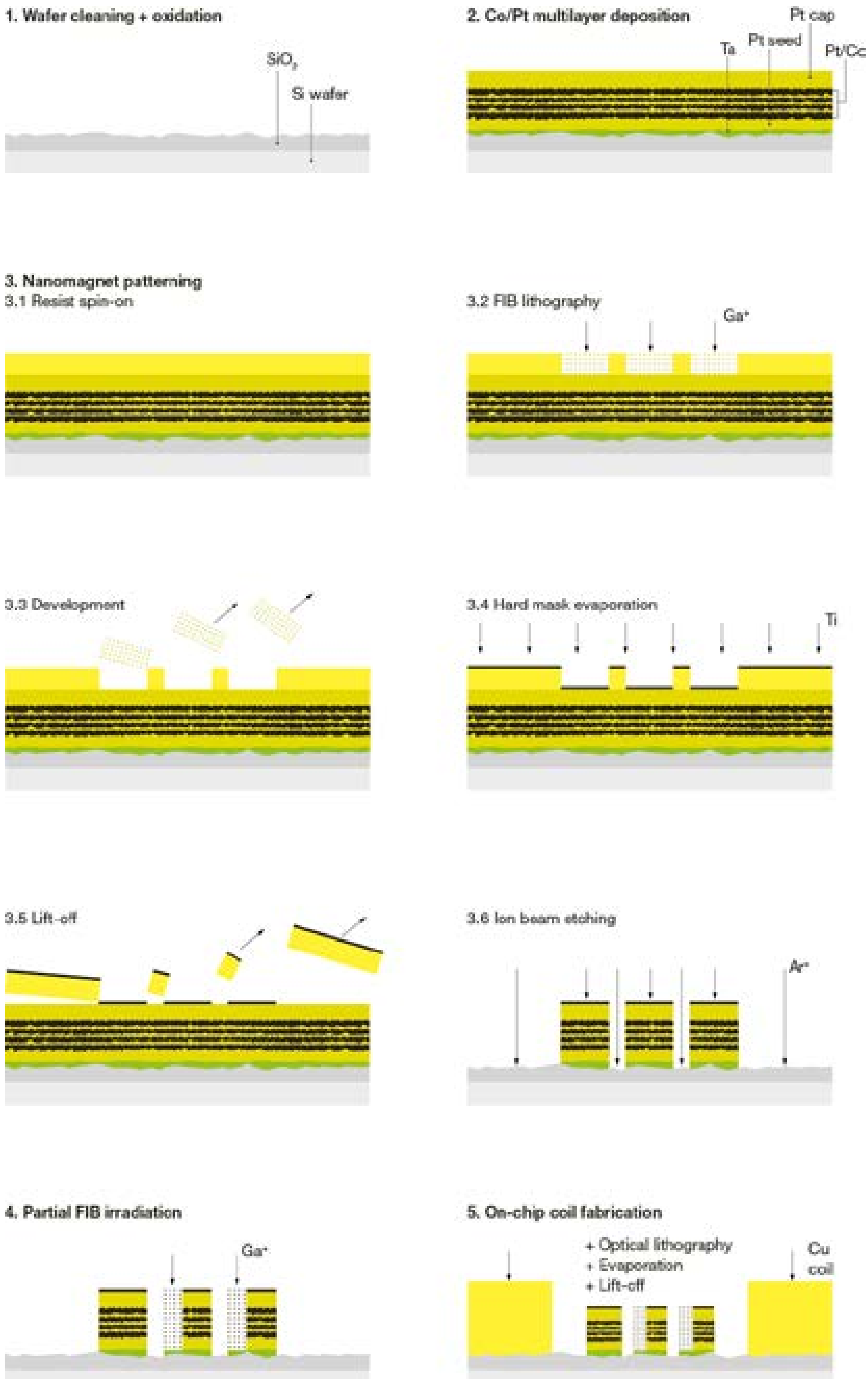
practical issues including power consumption. The smaller and more densely packed transistors are, the more power is wasted – not only when switching, but even in an idle state. These and other looming problems have created an opening for radical thinking. As the latest edition of the International Technology Roadmap for Semiconductors (ITRS) says: "Looking at long-term devices and systems (7 – 15 years horizon, beyond 2020), the 2013 ITRS reports on completely new devices operating on completely new principles amenable to support completely new architectures." In other words, it's time to consider a fork in the industry roadmap – if not several branching paths – to ensure that this foundational technology is not going to hit the wall. Groups around the world are probing a range of possibilities, even some that involve computing without transistors.



Magnetic computing now

The idea of magnetic computing goes back at least to the 1950s, and it engaged bright minds at research powerhouses including IBM and Bell Labs. Magnetic logic, however, was not viewed as being competitive with semiconductor-based technologies, which by the mid-1970s had already out-competed even the most successful magnetic technology, core memory. The idea never quite died, even as researchers moved on to greener pastures. Today, though, the approach under investigation at TUM truly could be considered, in the words of the ITRS, "completely new."
According to Dr. Markus Becherer, leader of a research team at TUM, computing based on nanometer-scale magnetic devices has some inherently attractive characteristics, ▷



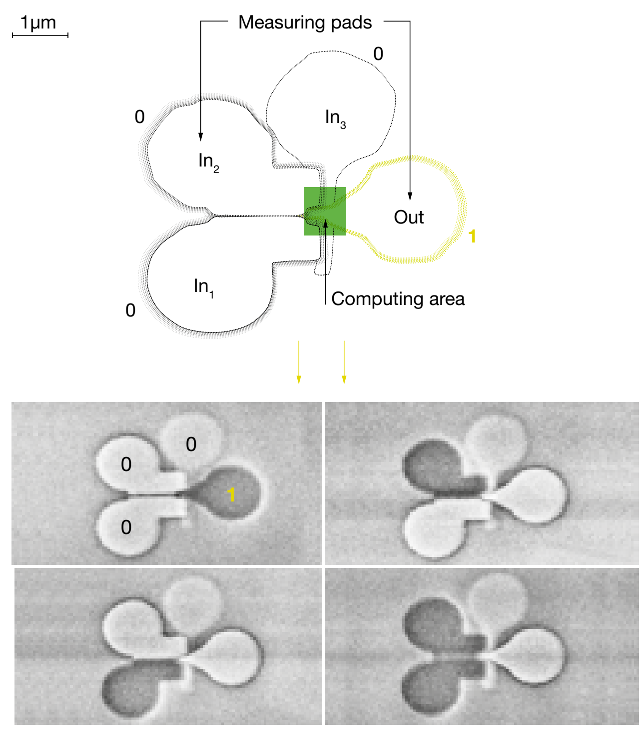


Picture credits: ediundsepp (source: TUM)

Stacking ten nanomagnetic gates yields a ten times higher area density

beginning with ultra-low power consumption. And it's fairly easy, he adds, to identify applications in which nanomagnetic technology could have advantages over CMOS, such as parallel computing, data mining and pattern matching. "The biggest questions arise," Becherer says, "when you think about all of the requirements that need to be fulfilled, all the numbers that have to be matched, to build a fully functioning and competitive system. If just one property fails to meet the mark – say, with regard to mass production, variability or manufacturing cost – then the technology cannot be exploited for applications." It's this big-picture view that motivates Becherer's team, based in Prof. Doris Schmitt-Landsiedel's Chair of Technical Electronics, and helps to prioritize goals for their experimental program.

Since 2009 the group has demonstrated several advances toward practical nanomagnetic logic. Key contributions have been made by doctoral researchers Stephan Breitkreutz-v. Gamm, Irina Eichwald, Josef Kiermaier, Xueming Ju and Gražvydas Žiemys. Also vital, from the start, has been collaboration with researchers at the University of Notre Dame and with TUM colleagues in Prof. Paolo Lugli's Chair of Nanoelectronics. Crucial early steps included novel techniques for fabricating nanomagnets and for characterizing the new breed of circuits that would employ them. By 2012 a new family of building blocks for digital integrated circuits – nanomagnetic logic gates – began to appear. With successive experiments, the researchers have strengthened the case that some future computer chips could be based on arrangements of nanometer-scale magnets. A major result in 2014 was the demonstration of a three-dimensional ▷



Magnetic force microscopy images of a 3D majority logic gate. In$_1$, In$_2$, In$_3$ and Out indicate the input and output nanomagnets (In$_3$ is located 60 nm below the others). The areas shown in the image are pads used by the scientists to measure the magnetic state of each magnet. The actual computing area is about 550 by 700 nm in size. Shown here is a NOR gate, which yields "1" whenever all inputs are set to "0" and "0" otherwise. For laboratory operation, the magnetization of the input magnets is set via copper coils on the chip. In practice, the magnets would be set by preceding magnets in the circuit.

The production process for nanomagnetic logic devices starts with a silicon wafer, onto which a multilayered sandwich of cobalt (Co) and platinum (Pt) is deposited via RF magnetron sputtering (1, 2). This multilayer film is patterned into isolated Co/Pt nanomagnets using focused ion beam (FIB) lithography for shaping the magnets and argon (Ar) ion beam etching to remove the remaining material (3.1 – 3.6). Partial FIB with Ga^+ ions is the key process to lower the magnetic anistotropy of the nanomagnets by disrupting the stable interfaces between the Co and Pt layers (4). The magnetization can then easily be set by an external magnetic field generated by copper coils, which are produced in a final step by optical lithography (5).

The most basic building blocks are around 30 by 60 nanometers in surface area

nanomagnetic device – implementing a so-called majority logic gate – that could operate in vertical stacks.

Devices based on this approach would compute not by switching electric currents but by controlling coupled magnetic fields – more specifically, through the influence of each nanomagnet's "stray field" and the propagation of tiny "magnetic domain walls." Thus, the devices would be non-volatile, meaning that logic elements could remember their states even with the system turned off. Drawing no current at all when idle, such circuits would consume very little power even when operating – and would waste next to nothing, since magnets don't "leak." An additional advantage is that they should be more resistant to electromagnetic radiation than CMOS integrated circuits, particularly at the short wavelengths of X-rays and gamma rays. Finally, the option of stacking large numbers of magnetic gates on top of each other might make them irresistible in terms of integration density: having ten gates stacked, for example, the density is ten times higher within the same footprint.

The researchers explain the underlying principle of the nanomagnetic majority logic gate with a simple illustration: Think of the way ordinary bar magnets behave when you bring them near each other, with opposite poles attracting and like poles repelling each other. Now imagine bringing several bar magnets together and holding all but one in a fixed position. Their magnetic fields can be thought of as being coupled into one, and the "north-south" polarity of the magnet that is free to flip will be determined by the orientation of the majority of fixed magnets. Gates made from field-coupled nanomagnets work in an analogous way, with the reversal of polarity representing a switch between Boolean logic states, or the binary digits 1 and 0. In the team's 3D majority logic gate, the state of the device is determined by three input magnets, one of which sits 60 nanometers below the other two, and is read out by a single output magnet. ▷

A fruitful collaboration

These advances in computing based on nanomagnets are the fruit of a longstanding collaboration between TUM and the University of Notre Dame in South Bend, Indiana, USA. The work builds on capabilities ranging from sophisticated simulations of magnetic behavior to innovative fabrication and measuring techniques.

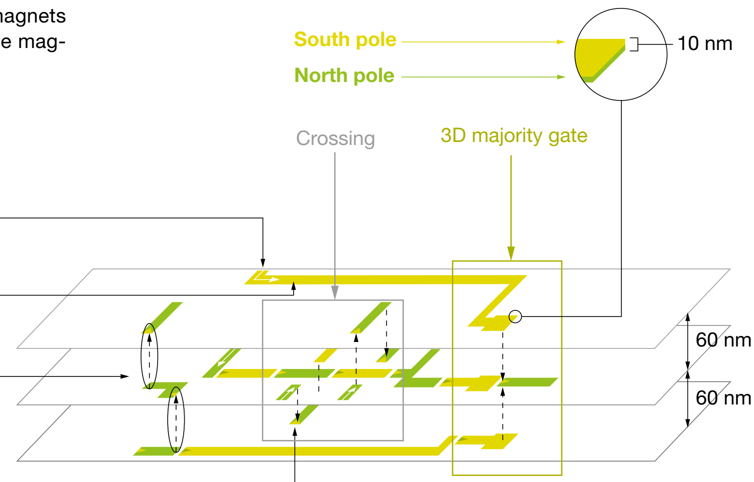
A central figure is Gyorgy Csaba, who did his doctoral research with Prof. Wolfgang Porod at Notre Dame. Csaba did the initial proof-of-concept simulations on nanomagnetic logic. He then moved to Prof. Paolo Lugli's Chair of Nanoelectronics at TUM but continued to provide modeling support for Notre Dame's emerging experimental program. He realized that similar ideas could also be tested with technology available just three buildings away, at Prof. Doris Schmitt-Landsiedel's Chair of Technical Electronics: specifically, the ability to grow cobalt-platinum multilayers and to pattern devices using focused ion beams. Markus Becherer took the lead in starting the experimental work there, while doctoral candidates in the Chair of Nanoelectronics did some of the important simulation research under Csaba's guidance.

Over the years, members of the TUM team have spent time at Notre Dame. Porod, as a Fellow of the TUM Institute for Advanced Study, has made many visits to Munich. And when Csaba eventually returned to Notre Dame as a research associate professor, the strong ties were kept up. The experimental programs at Notre Dame and TUM are based on different types of structures, different materials and different patterning techniques. Yet throughout, the researchers' partnership has been extremely productive, with mutual feedback and strong complementary contributions.

A team that thinks outside the box: Stephan Breitkreutz-v. Gamm, Markus Becherer, Gražvydas Žiemys and Irina Eichwald (from left) are investigating the potential of 3D nanomagnets for a radically new computing technology.

Picture credit: Filser

Cross-section through a 3D nanomagnetic device: Nanomagnets can be arranged in several layers. Signal transfer between the magnets happens via magnetic coupling fields, without wires.



The road ahead

There are several reasons why nanomagnetic logic can allow very dense packing. The most basic building blocks, the individual nanomagnets, will be around 30 by 60 nanometers in surface area and thus are comparable in size to individual transistors. Furthermore, where transistors need contacts and wiring, nanomagnets operate purely with coupling fields, requiring only on-chip copper coils to control the magnetic field of the nanomagnets. Also, in building CMOS and nanomagnetic devices that have the same function, it can take fewer magnets than transistors to get the job done. For example, a so-called full-adder demonstrated by the TUM team consisted of just five interacting magnets whereas, depending on the architecture, 20 to 30 CMOS transistors would be required. Finally, breaking out of the 2D design space with stacks of 3D nanomagnetic logic gates is a step with truly disruptive potential.

The 2013 International Technology Roadmap for Semiconductors gave some serious attention to magnetic computing

In its 2013 edition, the International Technology Roadmap for Semiconductors gave some serious attention to magnetic computing, in a chapter on "Emerging Research Devices." Soon after, the "Journal of Physics D: Applied Physics" published "The 2014 Magnetism Roadmap," which featured a review of nanomagnetic logic by TUM's Stephan Breitkreutz-v. Gamm. The challenges outlined in his paper are daunting, but the evidence and arguments in favor of this technology are compelling.

One of the most provocative observations is that the strict separation of logic and memory in the classic "von Neumann" computer architecture – which underlies most of the computers that have ever existed – is redundant if your logic runs on non-volatile nanomagnets instead of transistors. Thus, progress in magnetic logic might inspire, or require, rethinking some of the basics of computer science.

A higher priority for Becherer's team, however, is ensuring that there will be a constructive synergy between magnetic computing and CMOS. The best outcome they can envision is not for their nanomagnetic logic technology to "beat" the competition, but rather to join it.

Patrick Regan (TUM)

Picture credits: ediundsepp (source: TUM)