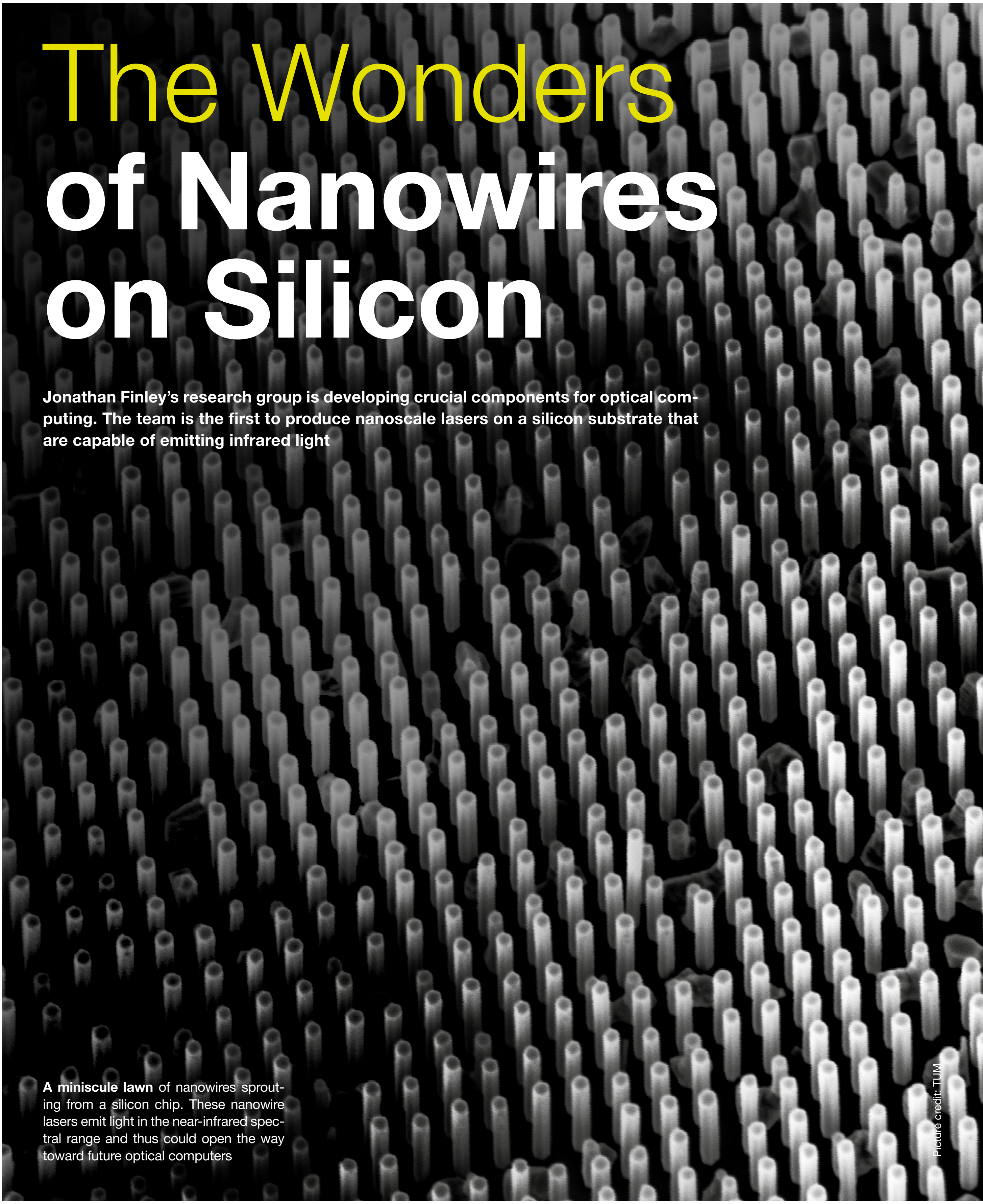
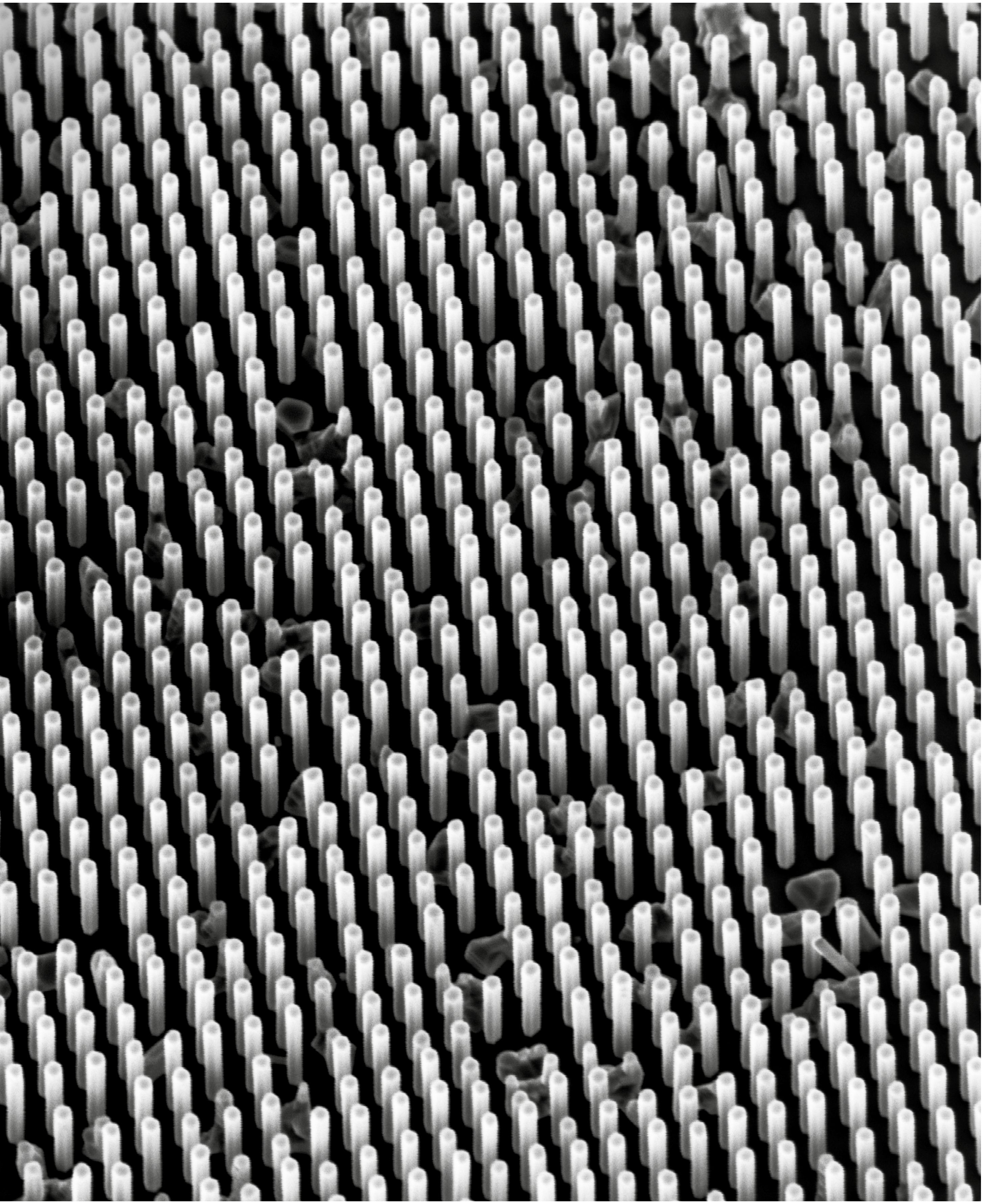
The Wonders of Nanowires on Silicon

Jonathan Finley's research group is developing crucial components for optical computing. The team is the first to produce nanoscale lasers on a silicon substrate that are capable of emitting infrared light



A miniscule lawn of nanowires sprouting from a silicon chip. These nanowire lasers emit light in the near-infrared spectral range and thus could open the way toward future optical computers

Picture credit: TUM



Zauberhafte Nanodrähte auf Silizium

Prof. Jonathan Finley, Direktor des Walter Schottky Instituts (WSI) der TU München, und seinem Team ist es gelungen, eine wichtige, bisher noch fehlende Komponente für optische Computer zu entwickeln: Sie züchteten erstmals auf einer Silizium-Oberfläche Laser im Nanobereich, die Licht im Infraroten erzeugen. Es handelt sich um Nanodrähte aus Galliumarsenid, nur ca. 300 Nanometer dick und etwa zehn Mikrometer lang, die direkt auf der Silizium-Oberfläche hochwachsen und dann zum optischen Pumpen mit Licht bestrahlt werden. Durch die Ummantelung mit einer fünf Nanometer dicken Schicht aus einer Aluminium-Galliumarsenid-Legierung konnten sie zum Lasern gebracht werden. Die Messungen der Garchinger Forscher zeigten, dass diese Core-Shell-Struktur die optische Effizienz um den Faktor 1000 erhöht, verglichen mit einem reinen Galliumarsenid-Draht.

Nanolaser als optisches Schaltelement

Hergestellt werden die Nanodrähte mithilfe von Molekularstrahlepitaxie. Damit lassen sich die Strukturen durch Selbstorganisation Atom für Atom aufbauen, indem man in einem Hochvakuum entsprechende Materialien verdampft und sich auf einer geeigneten Oberfläche absetzen lässt. Da es möglich ist, die Nanolaser exakt auf einem Silizium-Substrat zu positionieren, eignen sie sich zur Integration auf mikroelektronischen Chips, wo sie als optisches Schaltelement dienen können. Im nächsten Schritt entwickelten die Wissenschaftler ein Verfahren, die Nanolaser elektrisch zu pumpen, was für einen Computer vorteilhafter ist als das optische Pumpen. *Brigitte Röthlein*

Link

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For the first time in my scientific career, I was actually too pessimistic," concedes a smiling Professor Jonathan Finley, Director of TUM's Walter Schottky Institut (WSI). "But Benedikt Mayer, my Ph.D. student, was confident of success – and he was quite right. Perhaps I'm getting old!" The 41-year-old head of the Chair for Semiconductor Nanostructures and Quantum Systems is referring to research into nanowires made of gallium arsenide, only around 300 nanometers thick and about ten micrometers long. The plan was to turn this into a tiny infrared laser – something many research groups around the world had already attempted without success. Various researchers managed to fabricate the necessary nanostructures and pump them with energy, but dissipation to the nanowire surface was so fast such that lasing action could not be achieved – or at least never at the desired wavelength.

In November 2013, the Garching-based WSI researchers coated their nanowires with a passivation layer just five nanometers thick and set about putting it to the test. And, as it turned out: "We grew the sample on a Monday, and by Thursday of the same week, we were already able to show that it was lasing," recounts Finley. "I thought we would probably need to try out several variants, but then we tested the first sample and it worked straight away. It was one of those champagne moments. In fact, we really did open a bottle and toast our success."

Optical computing, here we come

This type of tiny laser is no gimmick, but a long-awaited breakthrough in the world of optical information technologies. Moore's law predicts that the number of transistors that can be incorporated in a computer chip will double every 18 months or so due to their steadily shrinking size. "However, we are gradually reaching the limit," declares Finley. "The Haswell processors on today's Intel chips use transistors measuring just 20 to 30 nanometers in size, which means just a few hundred atoms between the contacts. If it carries on like that, we'll soon be down to a few tens of atoms per transistor." Beyond that stage, making computers faster and, above all, more energy-efficient calls for entirely new approaches. One of the main ones is to transmit information between components optically rather than electrically. Electrons move along wires and tend to heat them up in the process. By contrast, a light beam offers a multitude of benefits, including high capacity to transport information and the ability to cross other light beams without disturbance – not so easy with electrical interconnects. Most of all, information technologies based on light bring speed – nothing in the world is faster than light.

Using light for information transmission requires optical components – meaning light sources, waveguides and photodetectors on the chip. The latter two components

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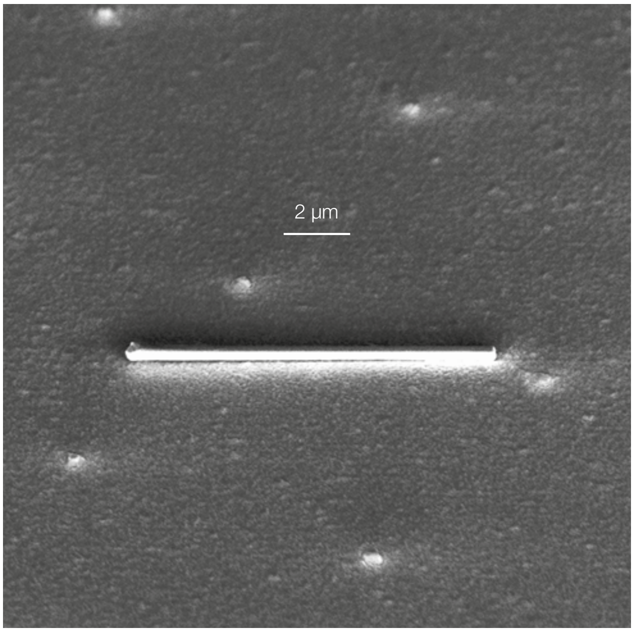
Scanning electron microscope image of a single GaAs-AlGaAs nanowire that has been removed from the silicon substrate and placed onto glass for study



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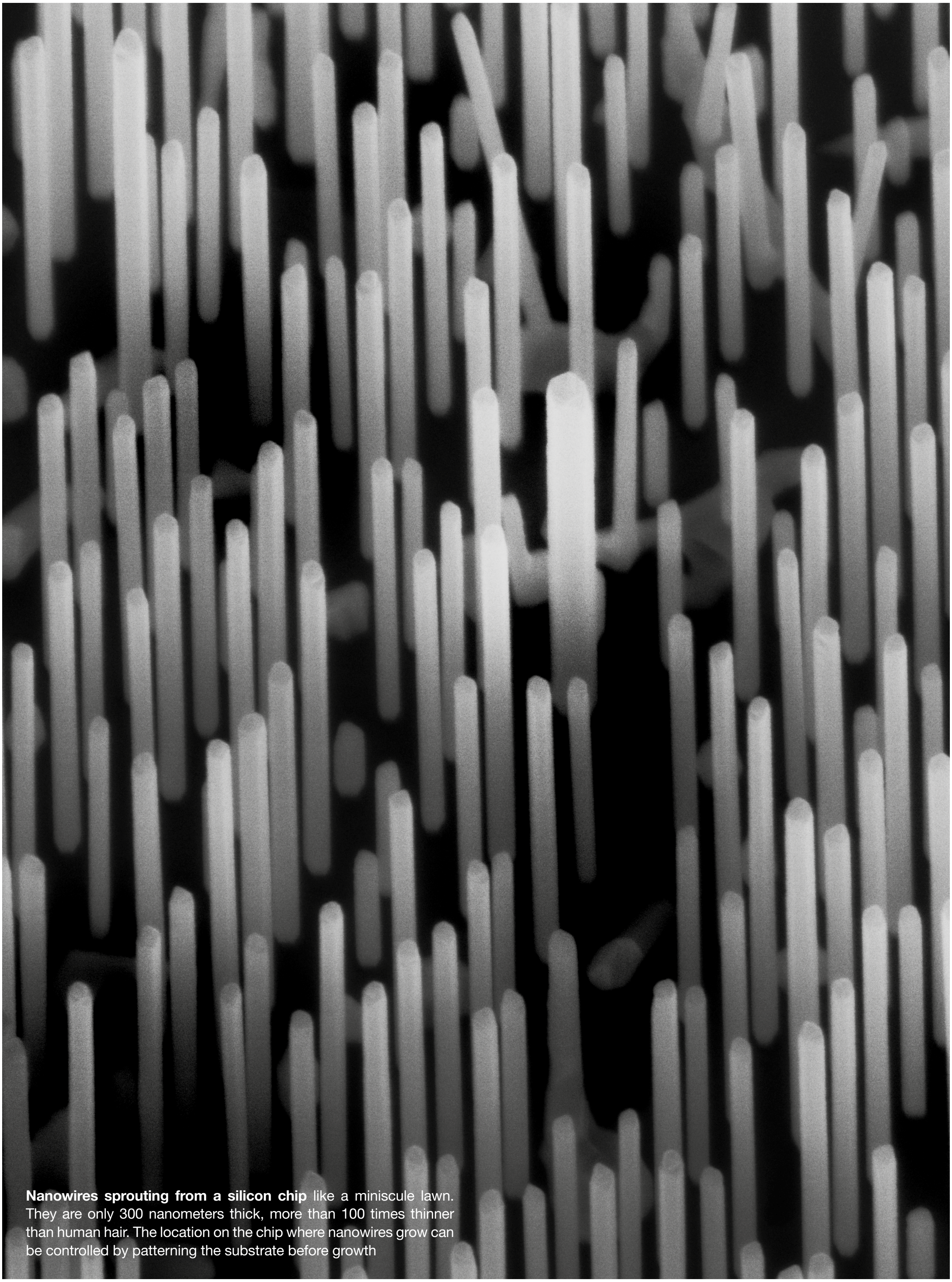
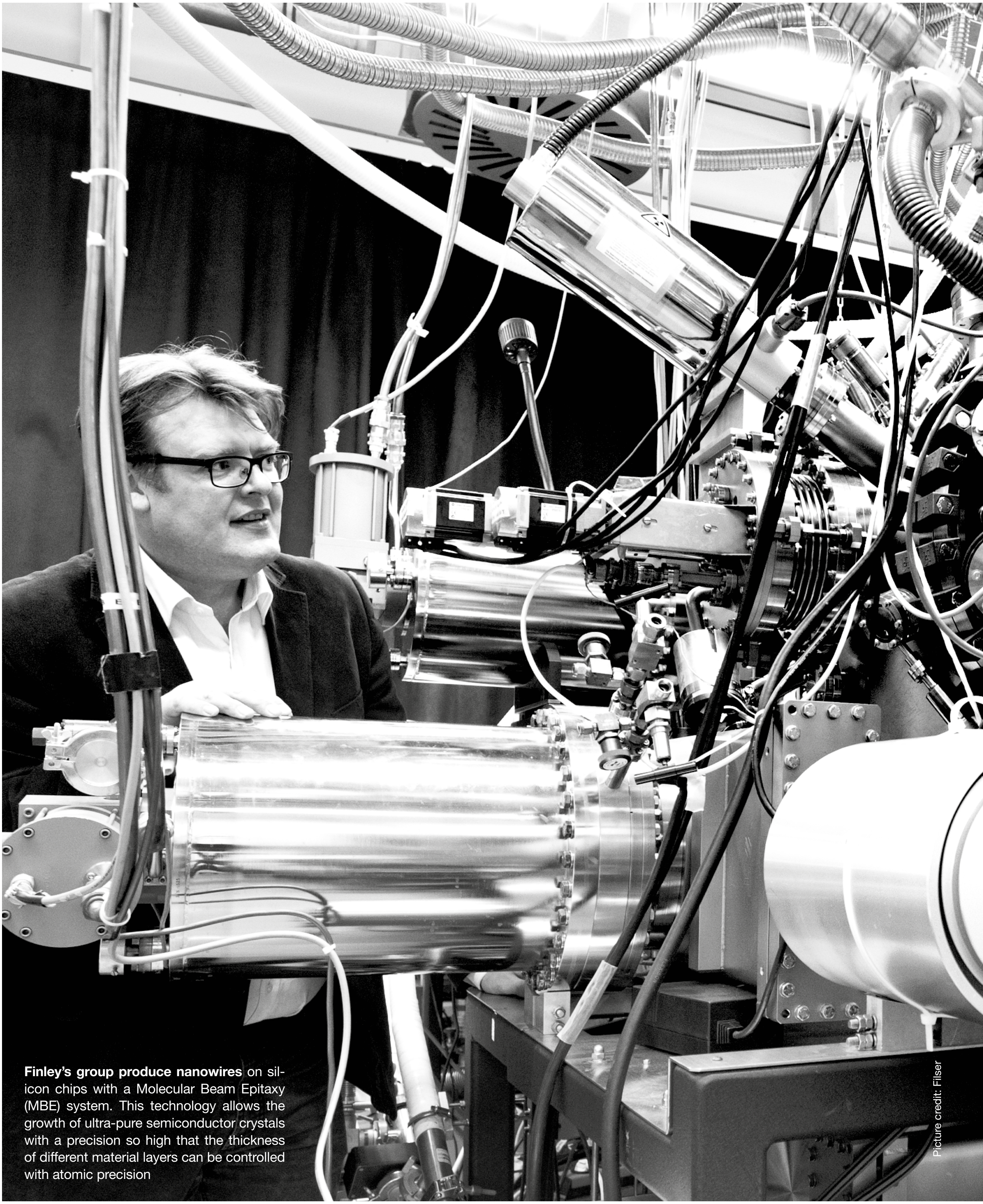
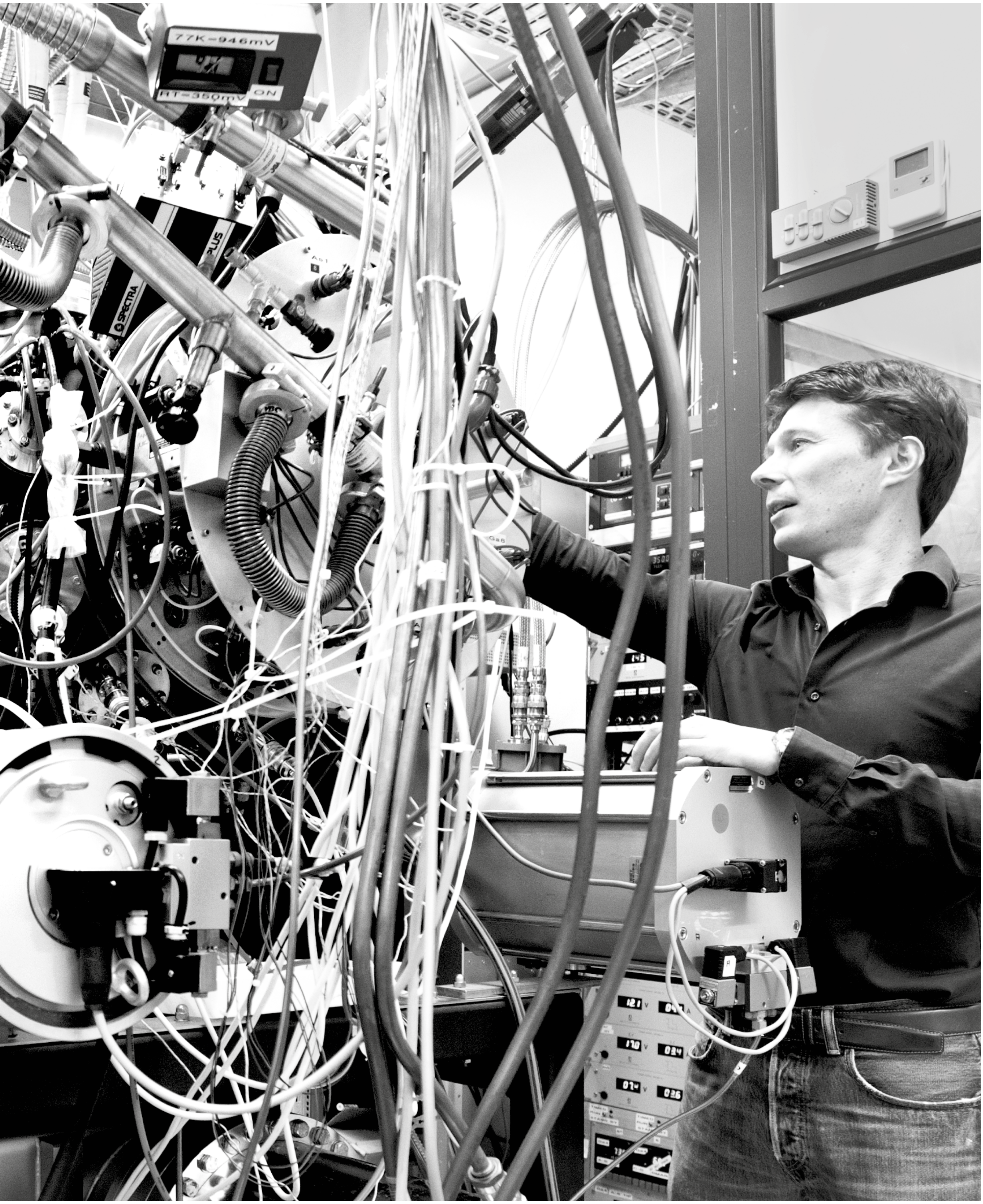


Nanowires sprouting from a silicon chip like a miniscule lawn. They are only 300 nanometers thick, more than 100 times thinner than human hair. The location on the chip where nanowires grow can be controlled by patterning the substrate before growth



Finley's group produce nanowires on silicon chips with a Molecular Beam Epitaxy (MBE) system. This technology allows the growth of ultra-pure semiconductor crystals with a precision so high that the thickness of different material layers can be controlled with atomic precision

Picture credit: Filser



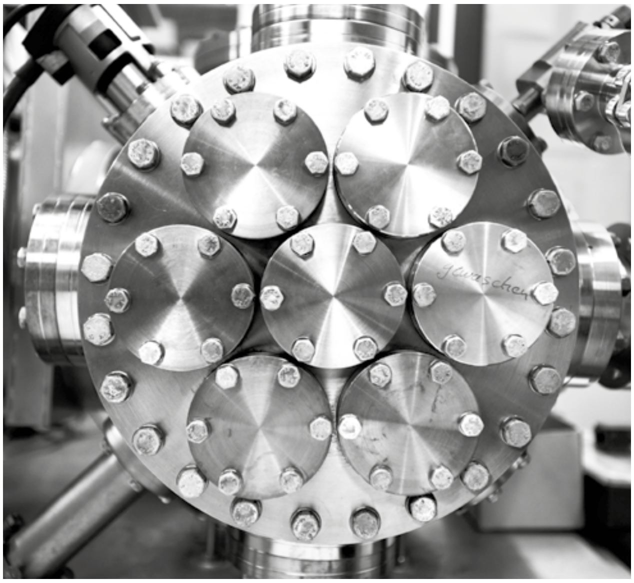
are already available, but growing the required high-performance light sources directly on silicon (Si) chip substrates previously posed a stumbling block for researchers. These sources must emit light at the correct wavelength – that is, in the infrared spectral region – since silicon structures are non-transparent for visible light. An infrared laser that can be directly integrated on a chip is thus precisely the missing link that computer manufacturers are looking for.

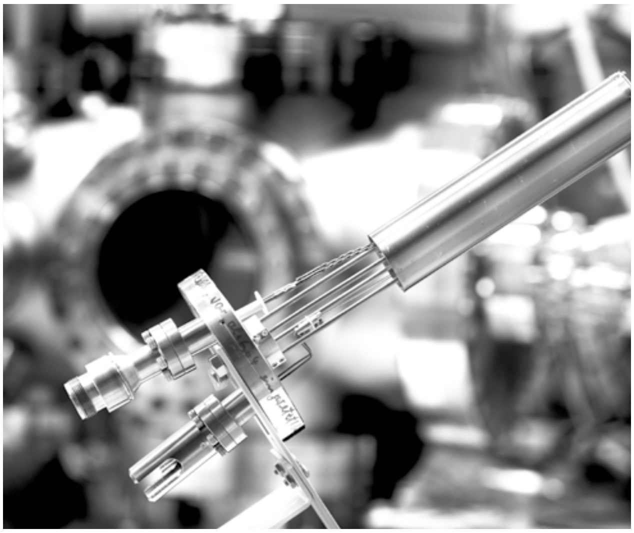
Building wires atom by atom

A freestanding nanowire that sticks out of a silicon chip like a tiny bristle and emits laser beams would be an ideal solution. So WSI research groups led by Finley and Professor Gerhard Abstreiter spent years exploring how to build nanowires – which can, in fact, be used for other purposes, too. By now, the researchers have pretty much perfected their method. Dr. Gregor Koblmüller and his students operate the molecular beam epitaxy (MBE) system, which allows the formation of these nanowires, with artistic finesse. They know how they can build up nanowires atom by atom by vaporizing the relevant materials and depositing them onto a substrate in high vacuum.

Ordinarily though, the vapor would condense over the entire surface of the chip, but this is clearly no way to produce nanowires. Essentially, nanowires are simply tiny monocrystals of semiconductor material, such as gallium arsenide (GaAs). If you supply both gallium and arsenic vapor and deposit these onto a silicon substrate, the natural tendency is to coat the whole surface and thus grow into a flat (planar) layer. “That wouldn’t be bad in itself, but it causes huge tensions at the interface with the substrate, which can only be relieved through the formation of a high number of crystal lattice defects,” explains Koblmüller. “These defects eat up a lot of energy, so we can’t build efficient lasers that way.”

The scientists in Finley’s team have solved this problem by growing the GaAs on a very small footprint instead of spreading it over a wider surface. “This means the material can grow upward in tiny columns,” reveals the British researcher. “The sharp rise in the surface-to-volume ratio of these nanocolumns means tensions that have built up can easily dissipate across the surface. Which allows us to grow the GaAs crystals on the silicon chip with almost zero defects.” To start with, the researchers exploited small ▷

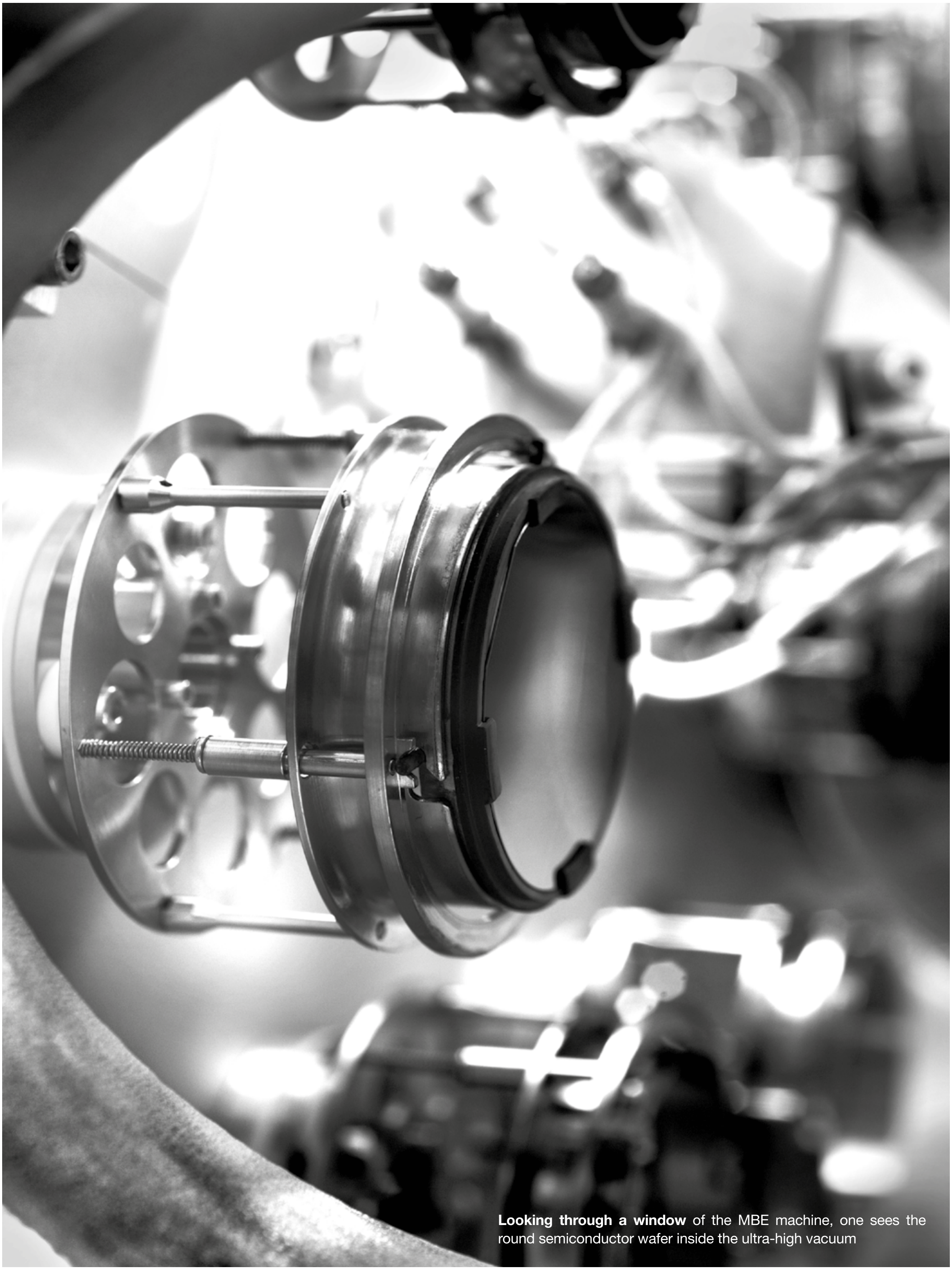




Inside the MBE system’s (top) ultra-high-vacuum chamber a Knudsen cell (middle) supplies ultra-pure beams of atoms to be deposited onto the chips. Max Bichler (bottom) examines a piece of wafer. One can see the area which contains nanowires with the naked eye

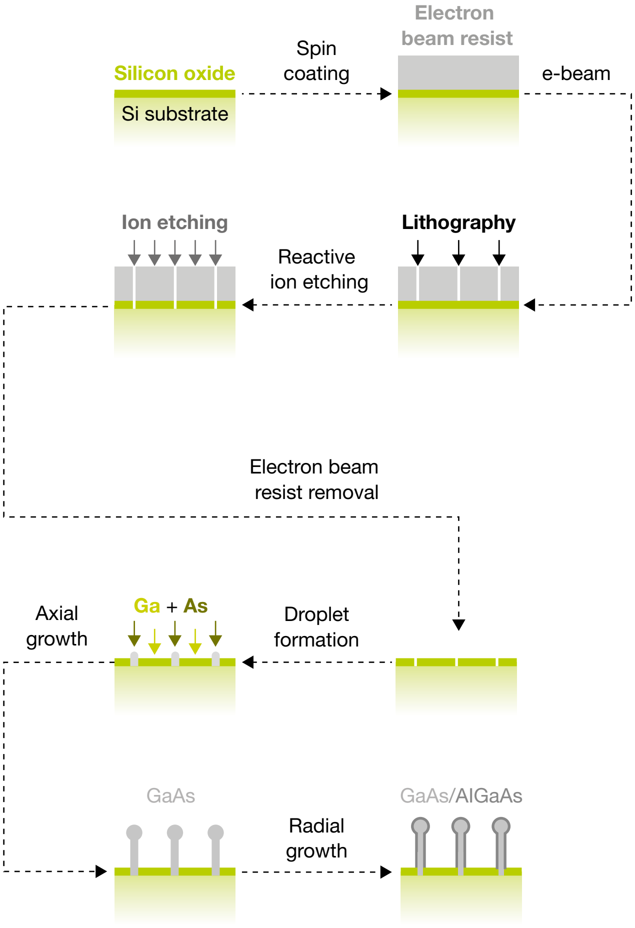
Right: In the laser laboratory, optical spectroscopy is used to analyze the properties of the semiconductor nanostructures. The measurements also allow scientists to test and optimize the performance of the nanowire lasers as external parameters such as temperature, etc. are varied

Picture credits: Filser



Looking through a window of the MBE machine, one sees the round semiconductor wafer inside the ultra-high vacuum

Picture credit: Filser/Graphics: ediundsepp



Nanowire production: Tiny holes are lithographically etched into a silicon oxide layer. Gallium and arsenide atoms deposited onto the chip can only grow upward from these holes. To reach the required optical efficiency to create laser beams, the nanowires are encapsulated with aluminum gallium arsenide

irregularities on the surface to seed the growth of these crystals. However, this was too random for them. So they began to use lithographic methods to etch tiny holes in the silicon oxide layer, which was specifically grown on the surface of the Si substrate. When gallium and arsenic atoms are deposited onto the chip under these conditions, the crystals can only grow upwards from these holes. “It works like a charm,” describes Finley. “The nanowires sprout from the chip like grass growing on a miniscule lawn. They are extremely pure and we can see through the electron microscope that they really are formed with great precision, layer by layer.” Koblmüller adds: “We are combining top-down and bottom-up procedures here. First we etch the holes – intervening from outside – and then we allow the monocrystals to grow, which is entirely a self-organizing process.” By now, the researchers know their way around the tiny wires – they can “mow” them with a piece of paper and then separate them; they can manipulate them with optical tweezers or use a polymer web to pull them out of the substrate (“just like waxing”) and move them from one site to another. And they can smooth off the end facets of the wire to produce a high-reflectivity mirror. Normally, every wire has a tiny drop of metal at its tip, which serves as the catalyst for its formation. To remove this, the team fills up the entire structure with a polymer, and can then etch away the tips with precision. The result is a smooth mirror, which is a key requirement for a good laser.

Wire with laser action

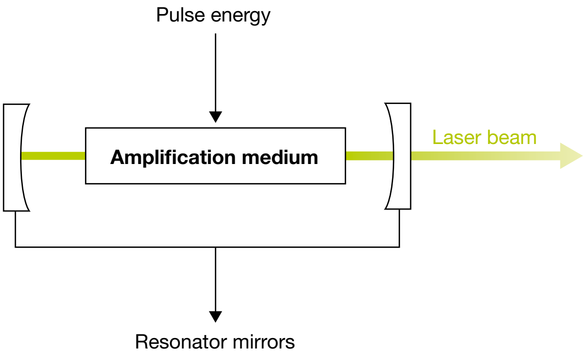
As exciting as the initial successes were, it was also clear that the nanowires alone would not suffice. Other research groups had already shown that energy pumped into these wires in the form of light was not amplified internally and then emitted again as a laser beam. Rather, it was found that the charge carriers released in the material discharged their energy again at the surface of the wires during recombination processes, without emitting light. So the WSI researchers began to consider ways of to prevent this effect. They decided to try applying a barrier to the surface of the nanowires to impede the charge carriers. Once again, Koblmüller’s expertise was called for. Together with Ph.D. student Daniel Rudolph, he devised a method of adapting the epitaxy process to permit radial growth. This way, the wires grew thicker rather than taller. The researchers then encapsulated them with an alloy layer of aluminum and gallium arsenide, forming a shell around the wire core. “This is only five nanometers thick, so equivalent to just 20 layers of atoms,” specifies Finley. “But our measurements showed that this was enough to increase the optical efficiency by a factor of a 1000.” And so the nanowire laser was born. GaAs is the optical medium inside it, while the outer layer serves purely as a barrier that prevents the charge carriers from reaching the surface and losing energy without emitting light. While laser activity was only detected at low temperatures to start with, it has now been shown that the nanowires emit infrared light even at room temperature.

A bright future

There is still one downside to the tiny lasers: they require optical pumping. This means that, for the wires to emit infrared laser light, they first have to be irradiated with visible light. This would not be ideal for future use in computers, where electric pumping would be preferable – so this is the next challenge facing the Garching-based researchers. They have already devised processes to make the nanowires electrically conductive by doping (i.e. adding impurities). If they form a contact with the surface, they can apply voltage and electrically excite the wires. In general, too, the scientists are aiming to optimize the lasers further by varying the outer layer and the layer separating the wire and substrate. Clearing all the hurdles in terms of technology and phys- ▷

The principle of the laser

In a laser medium, most of the atoms and molecules are in a largely de-energized state. If energy is pulsed into the medium, in the form of a light source or an electrical discharge for example, the atoms become energized, transforming to an excited state. This energy can be released by exciting them with suitable photons. The parallel mirrors at each end reflect the light back and forth. The photons then encounter other excited atoms and molecules and cause them to release their energy. More and more photons are cumulatively released in this way. The laser beam composed of parallel light waves is then emitted through one of the end mirrors, which is semi-transparent.



ics takes years of detailed work and a great deal of practical experience in this area. So it is particularly important to Finley that all the key equipment for producing and testing the nanostructures is available at the institute. "That is a major advantage. We've been able to grow, process, structure and measure the wires right here on site. No need to wait until a collaboration partner can deliver samples – we are in the advantageous position that we can do it all ourselves. That means we can be innovative and react as quickly as possible to new requirements. If something doesn't work, we can tailor the properties of the nanowire and try again." The WSI researchers also work closely alongside the Nanosystems Initiative Munich (NIM) excellence cluster: "Nanoscience is exceptionally well established here in Munich, and one simply cannot overestimate the advantages of this strong base of expertise and capabilities," emphasizes Finley.

Beyond computing, the nanowire lasers also have the potential to advance other fields, for instance providing a compact light source for biophysics or in environmental and biosensor applications. And the team has already received initial inquiries about using them as a tool in microsurgery or dentistry. However, Jonathan Finley is proceeding with caution: "I told them we're not at a point where we could sell anything yet – that might still take another couple of years."

Brigitte Röthlein

Professor Jonathan Finley and his team were among the first scientists to produce semiconductor nanowire lasers in the near infrared spectral range. Such nano-photonic technologies could pave the way toward chip-level optical information processing devices for future optical computers. Moreover, they also provide potential for use as a nanoscale light source that could be used in other fields, such as biophysics and nanoscale photonic sensing

Picture credit: Filser