ULRICH GÖSELE’s fi rst success ini-
tially put him completely off
the idea. Back in the mid-1990s,
while still at Duke University on the
east coast of the US, his team suc-
cceeded in making silicon light up,
and thus in creating one of the nec-
essary conditions for the electronics
that may rule the future. Some sci-
ettists, at least, hope that optoelec-
tronics will one day be able to reme-
dy the shortage of space on computer
chips. Then photons will take the
place of electrons in interacting with
bits, and allow even more computing
power in very little space.

But that will take a few more years,
in any case. In the meantime, physi-
cists and materials scientists are still
investigating the tools that photonics
offers: photonic crystals, for instance,
that conduct light in much the same
way that copper conducts electricity.

And light sources that can be pro-
duced with tried and tested methods
— methods such as those the chip in-
dustry routinely uses to etch transis-
tors in silicon. Since it is so good at
this, it is expected that optoelectron-
ics, too, will use as many silicon
components as possible. For this rea-
son, scientists are working on diodes
and lasers made from this element.

That’s how things were some 17
years ago, too, when Ulrich Gösele
first examined the special optical
properties of extremely small silicon
structures. “We had used electro-
chemical means to etch tiny, unor-
dered structures in a silicon block.
Actually, in doing so, we investigat-
ed how nanostructures can be pro-
duced with this method,” says the
physicist: “It was more or less by
chance that we then determined that
this porous silicon light already be-
gins to absorb in the red range, and
not only in the invisible infrared
range, like normal silicon.” This in-
dicated that the silicon sponge could
also produce visible light. Unfortu-
nately, optical fi bers do not conduct
visible light particularly well, so a
silicon sponge that glows red is not
very interesting for the chip indus-
try. In addition, the silicon sponge
ages and gradually loses its lumi-
nosity – but at least they were on to
something.

“However, the article that we sub-
mitted to APPLIED PHYSICS LETTERS
on this was initially rejected by a re-
viewer,” recalls Gösele. So he and his
colleagues were all the more sur-
prised when, a few months later, a
very similar article appeared in pre-
cisely this magazine – published by a
British group and waved through by
another reviewer. “So I fi led a com-
 plaint,” says Gösele, his voice un-
wavering. And thus his silicon sponge
became public, too, although a few
months after the British publication.

PLAYING HARDBALL
Since Ulrich Gösle’s team had sub-
mitted its paper fi rst, it wanted to at
least secure the patent. This was in
line with applicable law, but not with
the interests of the British Ministry
of Defense, which had fi nanced the
competing article. The Ministry fi led
a lawsuit to rescind the patent for
the silicon sponge: “Their attorneys
really played hardball,” says Gösele
with an almost apologetic smile: “If
you can’t stick it out, you’re ruined.”
He gave up the patent that had al-
ready been granted.

No other material in the
electronics industry is handled
with such routine as silicon.
The industry would like to
use this proficiency when
computers one day use light
to perform their calculations.
The only problem is that,
to date, there are no viable
light sources made of
silicon. ULRICH GÖSELE,
Director at the MAX
PLANCK INSTITUTE OF
MICROSTRUCTURE PHYSICS,
and his colleagues have
now produced silicon diodes
that may also be customized
for use in optoelectronics.

Play of Light on a Microchip

An oven for very
special baked goods:
Vadim Talalaev (left)
and Andreas Langner
heat up nanostruct-
ured materials
in this device.
Today’s printed circuit board: Here, data still travels through the circuits as photons. That frustrated me so much that I initially just steered clear of the whole subject.” Temporary because, more than 10 years later, Ulrich Gösele and his colleagues have indeed taken up the subject again at the Max Planck Institute in Halle. “This research had slackened a bit in the intervening time — and not just for us,” says Gösele: “But it is now booming again.” The fact is that there is, as yet, no industrially usable silicon dioxide, or even a silicon laser that the chip industry could feasibly use in optoelectronics. This is due primarily to the fact that, from a physical standpoint, silicon is far from being the material of choice for a light source.

In order for a material to emit light, its electrons must first take up energy, which can be supplied to them in the form of, for instance, electrical energy. When this happens, they jump from a lower energy level to a higher one — with a kind of energy springboard. From there, they fall back to the lower level and release their excess energy, in the best case as light, or in physical terms, as photons.

With a semiconductor such as silicon, this is slightly different: When one of its electrons is excited, for example by electricity, as in a diode, or by light, in a solar cell, it not only leaves its energy level, but also its atom. It falls in with the herd of electrons that conduct electricity in a semiconductor, and belongs to all atoms, and to none. It leaves a hole in its original atom, creating a positive charge there. However, the electron of an adjacent atom quickly fills this hole, so the hole, too, is essentially distributed across the entire piece of silicon. Now, if an excited electron releases its energy again, it falls into one of the holes.

One requirement for the electron jump is that the energy levels — energy bands, in the case of a metal (see box) — lie favorably. Favorably means that the electron must whirl through the metal with the same momentum before and after the jump. Put simply, it must not change its speed or the orientation of its orbit while it takes up and releases energy. Quantum mechanics prohibits this, and this applies to both the upward and the downward jump.

But physicists are trying to change this. A kind of the indirect band gap. Peter Werner, Vadim Talalaev and their colleagues at the Max Planck Institute in Halle have mastered the tricks that help the silicon electrons jump. For example, the researchers recently constructed a light-emitting diode based on semiconductors. Silicon, however, is just one component in it: as in a sandwich, the scientists alternated nanometer-thin layers of silicon with a dash of antimony and germanium, stacked one on top of another. Such a sandwich structure is called a superlattice because a second array lies above the crystal lattice of the semiconductor. The germanium-silicon superlattice lights up because, in the adjacent germanium layers, the electrons of the silicon find suitable holes into which they can fall, creating a luminous trail.

Before Vadim Talalaev enters the lab in which he and his colleagues stack the semiconductors to form such a sandwich, he slips blue plastic covers over his shoes. Considering that scrupulous cleanliness is crucial for the room where the scientists stack silicon and germanium into superlattices (even atomic dirt can extinguish the diodes’ light), that is a very modest effort to keep the room clean. That is also why the equipment in the middle of the room is surrounded by a heavy curtain made of transparent plastic strips the width of a hand, behind which an extractor sucks dust and lint out of the air. This is where the tail system for molecular beam epitaxy stands. Two steel chambers, one of which, with its observation window, is reminiscent of a diving bell. Except that it is studied all around with cables and metal poles of varying thicknesses. In front of one side sits the second cylinder-shaped chamber, like the boiler of a steam engine. This is where the physicists feed the wafers, shiny disks of silicon, into the equipment.

After the pumps at the foot of the system have suctioned the air out of the lock for several hours, at the physicist’s command, a gripper arm manipulating wafers into the main chamber. An ultrahigh vacuum is at work here, which means that only a few hundred million molecules are zipping through the container. While that may still sound like a lot, it is billions of times less than the number we draw in with each breath. The researchers now alternately evaporate silicon, antimony and germanium from various crucibles. At the same time, they cool the silicon disk so that the gaseous substances condense on it. Estimating when the layer has precisely the right thickness is part of the art of experimenting. At least calibration curves offer the scientists a guide to how much of a certain material builds up in how much time.

The layers of germanium must not exceed a thickness of five nanometers, on average, and those of silicon not much more, in order for the superlattice to light up. Such a thin germanium layer forms a quantum dot whose electronic properties resemble those of an individual atom (see box). “The quantum effects that occur in the nanometer range make this research quite interesting for us,” says Ulrich Gösele.

One of the effects is that the electrons of adjacent silicon layers tunnel through the germanium layer that separates them. In doing so, they perform the form the same feat that allows Harry Potter and his fellow wizards to access platform 9 3/4, where the Hog- warts Express picks them up to take them to wizard school: they pass through a wall that we would bounce off of like a rubber ball. After all, we can neither perform magic nor are we small enough that the laws of quantum mechanics apply to us.

MINIBAND MAKES SUPERLATTICES LUMINESCENT

The tunnel effect is what makes the silicon-germanium superlattice a visible light source. Sandwiches made of thicker layers of both semiconductors also light up, but only very weakly because it is difficult for the electrons to reach the holes in the germanium. Unlike in a superlattice made of nanometer-thin layers: because the silicon layers find each other here by tunneling, they form an energy band that also extends across the germanium layers. Physicists call this a miniband, to distinguish it from the normal bands in the met- als. “The miniband of the silicon now lies in such a way that its elec- trons can easily jump from silicon to germanium,” says Talalaev. In doing so, they release energy — and the superlattices light up.

And it lights up quite well. “One diode from our silicon-germanium superlattice achieves a quantum effi ciency of 0.04 percent for infrared light,” says Talalaev. The quantum efficiency indicates how efficiently the diode converts electricity to light. Although 0.04 percent is just one- twentieth of the efficiency achieved by light-emitting diodes in a flat screen display, it is already 100 times more efficient than other nanodiodes composed of silicon and germanium.

It was also by coincidence that the physicists in Halle discovered that minibands form in stacks of thin germanium and silicon layers and thus boost the luminosity of the germanium quantum dots: they had ac- tually wanted to produce germanium quantum dots that are even thinner than the germanium layers in their diodes — but most importantly, they were to be kept at a distance from...
Silicon already lights up here – but not in a diode, as optoelectronics would require. ‘Then we vapor deposited the germanium quantum dots with an atomic layer of this material. This brought them not just one, but two advantages: first, there are five electrons dancing around in the outer shell of antimony atoms (which is chemically related to arsenic), rather than just four, as in silicon. In contact with silicon atoms, these additional electrons increase the electrical activity of the material – there are simply more electrons available to produce light.

Second, at the boundary between silicon and germanium, antimony acts like a tensile,’ says Talalaev. So it mediates between the two elements by reducing the surface tension between them. The atoms of the silicon cannot, in fact, be stacked neatly on top of the germanium atoms because their crystal lattice is somewhat smaller. Without antimony, the arrangement of the silicon continually gets disarranged and cracks appear. The electrons that want to jump from the silicon to the germanium then tend to fall into the cracks. When this happens, they do not emit light – that is what quantum mechanics dictates. Rather, their energy is released as heat. The antimony layer mediates between silicon and germanium in such a way that they positively cling to each other. As a result, far fewer excited atoms are lost at the boundary of the two semiconductors, and the quantum efficiency increases. This method is now even protected by a US patent.

“A silicon diode with our efficiency would be sufficient for optoelectronics,” says Talalaev. But for potential applications, it would be better if the material could be used to build, not a mere light-emitting diode, but a laser. Many scientists around the world are working on silicon lasers. Researchers at the University of California Los Angeles recently processed silicon into such a bright light source for the first time. “But they need another laser to supply the silicon laser with energy, or to pump it, as it is called in the field,” says Ulrich Gösele. The pump laser supplies the silicon with the energy it needs to produce light of this quality itself. “I don’t believe that has any future for applications,” says Gösele.

TUNNELLING INTO THE QUANTUM POT

In atoms and molecules, electrons know at least approximately where they belong: they travel in orbitals – balloon-shaped spaces that are grouped around a nucleus. Where the orbitals lie and what shape they have depends on the energy of the electrons. If the electrons take up energy, they jump from one energy level to the next and, in doing so, switch orbitals.

In metals, for instance in a silver coin, where countless atoms are joined together, the orbitals extend across the entire coin. The energy levels of each individual atom merge with the corresponding levels of the billions of other silver atoms to form bands. The electrons that sit in the uppermost band can move freely through the coin, making metals outstanding conductors of electricity and heat.

In silicon, this can’t be done very simply. Silicon is a semiconductor: there are no electrons in the band that would grant the electrons freedom of movement. A surge of energy must first put them there. In a solar cell, it is sunlight that provides this energetic surge.

In very small piles of a semiconductor, the band structure dissolves into individual energy levels again. This makes them similar to individual atoms, which is why physicists call such piles quantum dots. Such piles comprise only a few thousand atoms. The smaller they are, the fewer energy levels electrons find in them and the greater the distance between the individual levels is. Therefore, in small quantum dots, electrons need higher-energy light to jump from one level to another than they do in larger ones – so they also emit higher-energy light.

Quantum dots are interesting for science because quantum effects can be observed in them – for instance in germanium quantum dots that are embedded between silicon layers. There, the silicon electrons find free energy levels that lie lower than their own. The quantum dot thus appears to them like a pit into which they fall. And the smaller the quantum dot, the higher its walls are and the more energy the electrons need to get back out of them.

In computers that operate with photons rather than electrons, quantum dots could serve as light sources that emit individual photons. Furthermore, the color of their light can be controlled via their size. And sometimes quantum dots are even made to do something – such as silicon – a viable light source.

It could have just as well come from a waffle iron – but it is a superlattice of silicon quantum dots in silicon dioxide. The recipe is the work of Margit Zacharias. When an atom or molecule consists of two or more elements, it is possible to vary these elements in such a way that they positively cling to each other. As a result, far fewer excited atoms are lost at the boundary of the two semiconductors, and the quantum efficiency increases. This method is now even protected by a US patent. “A silicon diode with our efficiency would be sufficient for optoelectronics,” says Talalaev. But for potential applications, it would be better if the material could be used to build, not a mere light-emitting diode, but a laser. Many scientists around the world are working on silicon lasers. Researchers at the University of California Los Angeles recently processed silicon into such a bright light source for the first time. “But they need another laser to supply the silicon laser with energy, or to pump it, as it is called in the field,” says Ulrich Gösele. The pump laser supplies the silicon with the energy it needs to produce light of this quality itself. “I don’t believe that has any future for applications,” says Gösele.

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of silicon dioxide. Neither the oxygen nor the silicon feels chemically “at home” in the mixed oxide, and the heat in the furnace would give them the energy to arrange themselves as needed. When Margit Zacharias, back in Halle, presented the recipe to her then-boss, Ulrich Gösele, he was immediately convinced: “Don’t tell anyone about this,” he said to her. There was too great a risk that someone would pick up her recipe and be able to implement it faster. “I immediately sat down, wrote down the idea and got the signatures of two witnesses to attest to it,” adds Margit Zacharias.

The scientist was, in fact, the first to realize her creation of silicon nanocrystals. Not only do the silicon crystals form exactly the way she imagined it – they are all nice and round, nearly the same size, and they line up in orderly rows. “We can even control the spacing of the crystals in the layer through the oxygen percentage,” says the physicist: “And their size by applying the mixed oxide thicker in some places and thinner in others.”

Here, too, the size of the crystals is key. “Sometimes I imagine that the electrons and the holes in the nanocrystals simply can’t avoid each other,” says Margit Zacharias. That’s why they can find each other more easily and emit a flash of light when they meet. How tiny the crystals are also determines what color the quantum dots luminesce: crystals measuring two nanometers emit orange-red light, and if they measure four nanometers, they radiate in the near infrared.

It is again a quantum effect to which the nanocrystals owe their luminosity – quantum confinement. Regardless of whether one nanometer or four, all of the crystals are so tiny that their electrons and holes no longer have much freedom of movement. So little, in fact, that it is possible to precisely determine their location. Quantum mechanics comes into play here, which is also the reason why the nanocrystals are quantum dots. A Tunnel through the Insulation Layer

Heisenberg’s uncertainty relation allows only the location or the momentum (in simple terms, the speed) of a particle to be determined precisely – the respective other parameter remains an approximation. That is why the electrons in the quantum dots take on a large range of momenta – they establish the measurements of the crystals at a location. There are also momenta in this spectrum that close the silicon’s indirect band gap so that the electrons can fall into the holes and emit light. Thus, the nanocrystals fulfill an important condition for being able to build a diode or even a laser from them. But the trick that at least partially eliminates the indirect band gap also creates a new problem: as an insulator, the silicon dioxide not only traps the electrons and holes in the nanocrystals, but it also prevents any from penetrating into the crystal from outside. That is disadvantageous when electricity is to supply the energy for illumination. “So the holes and electrons must tunnel through the silicon dioxide layer,” says Lorenzo Pavesi. “And the oxide layers around the nanocrystals are, as yet, still too thick.”

Furthermore, they must simultaneously bring the charge carriers into the quantum dots so that they unite with a flash of light. If they tunnel into the crystals in succession, they quickly disappear into the imperfectly formed surface of the nanocrystals. But Pavesi already has some ideas for solving these problems. “Of course I can’t reveal how we intend to do that,” he says: “But it looks promising.”

Margit Zacharias is not quite as optimistic: “We have had only contradictory results so far on whether the nanocrystals are suitable for a laser,” she says: “But I am no longer following this topic now because I am more interested in the charge storage possibilities at the moment.” So Margit Zacharias has already identified another potential use for the nanocrystals: as storage nodes in conventional electronics. Then it wouldn’t matter whether physics continues to resist a viable silicon light.