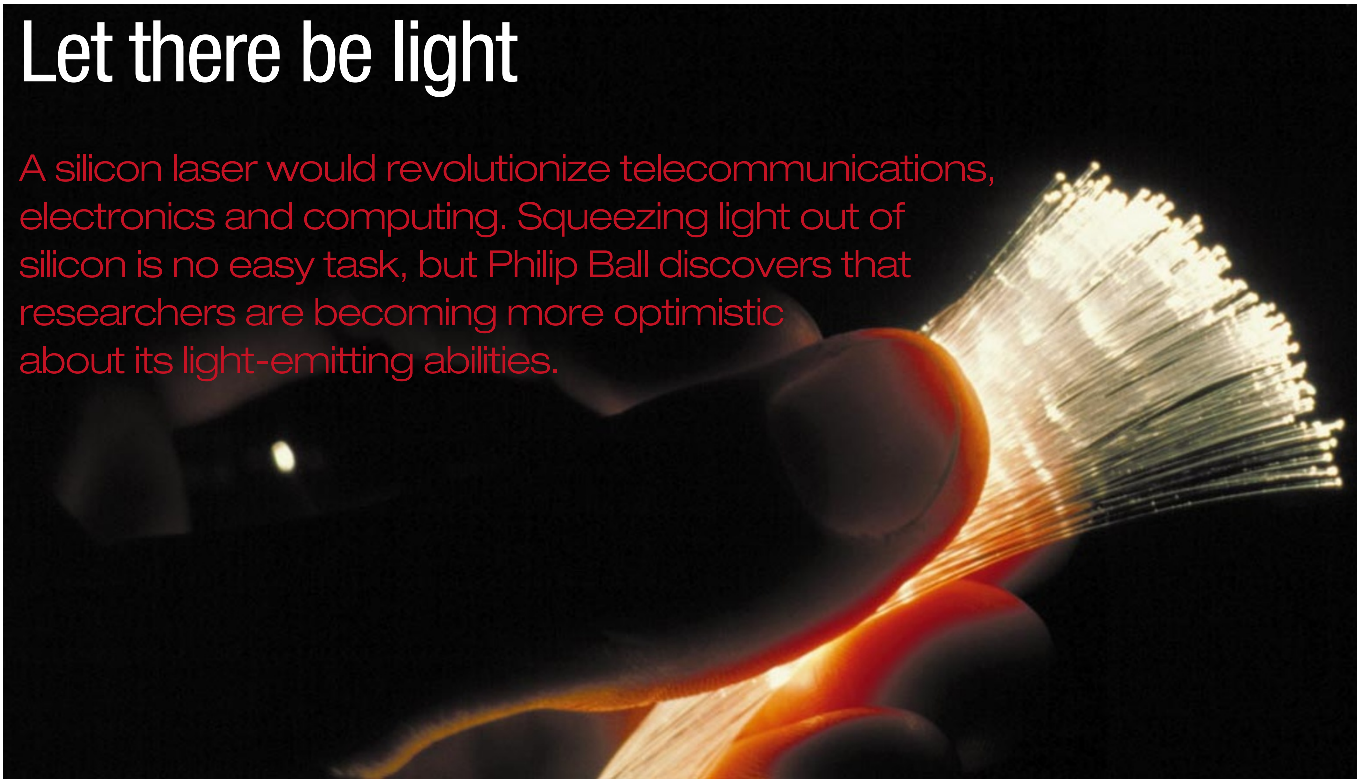
Let there be light

A silicon laser would revolutionize telecommunications, electronics and computing. Squeezing light out of silicon is no easy task, but Philip Ball discovers that researchers are becoming more optimistic about its light-emitting abilities.



WILL & DENI MCINTYRE/SPL

The information age suffers from a split personality. Deep beneath the ocean's surface, photons of light stream through optical fibres, carrying voice and Internet traffic between continents. But before routing devices, computers and telephones can use the data, this light-borne information must be converted into electronic signals. With entirely optical computers unlikely to replace electronics in the near future, this uneasy marriage of electrons and photons is likely to persist for some time.

Improving the interface between silicon electronics and photonics is high on the agenda in the field of optoelectronics. Some researchers believe that the solution lies in reforming silicon's character. Given patience and diligence, they say, the world's favourite semiconductor can be coaxed into emitting light. "If an all-silicon laser could be created, it would revolutionize the design of supercomputers and lead to new types of optoelectronic devices," says Leigh Canham of biomaterials company pSiMedica, a spin-off from the UK Defence Evaluation and Research Agency (DERA). And if recent progress continues, that revolution may not be far off.

Communication breakdown

At the moment, laser diodes are used to turn electronic signals into light pulses. These miniature lasers are built from layers of different semiconductors, named III–V alloys after the columns of the periodic table from which their constituents come. Positive and negative charge carriers move into thin layers within the laser known as ‘quantum wells’. Here the carriers recombine, releasing their energy as a photon of light.

But it is difficult to incorporate III–V alloys into silicon circuits. The two do not fit together because the spacing between the atoms in the two materials, known as the lattice constant, is different. The ideal laser diode for optical telecommunications — a blend of indium, gallium, arsenic and phosphorus, denoted $In_xGa_{1-x}As_yP_{1-y}$ — illustrates the problem. This material emits light at a wavelength of about 1.5 micrometres, which is the optimum for transmission through glass optical fibres, but has a lattice constant that is 8% bigger than that of silicon.

This means that atoms at the interface between the two materials do not match up, and line-like distortions form in the semiconductor. "Dislocations form near the interface and then thread through the III–V layer," explains Vincent Crespi, a physicist at Pennsylvania State University. Because this layer is thinner than the silicon substrate, the light-emitting III–V material incurs most of the deformation, and the resulting defects

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Glowing future: Leigh Canham (left) and Vincent Crespi hope to make silicon optoelectronics a reality.

severely degrade the layer's electrical conductivity.

As a result, semiconductor laser diodes must be kept separate from silicon circuits, which hinders the constant drive within the electronics industry to reduce the size of its circuitry. Separate lasers introduce further problems when chips are connected together, because achieving and maintaining precise alignment between the chips and the light sources becomes more complicated. It would be far better if light-emitting devices could be integrated directly with silicon chips.

That would be simple if silicon itself emitted light. But normal 'bulk' silicon does not, for a subtle reason. Semiconductors emit light when their electrons jump between energy levels. The size of the energy gap between these states — known as the band gap — determines the wavelength of the photon emitted.

Silicon's band gap corresponds to light with a wavelength of 1 μm, which would be fine for fibre-optic transmission. But silicon has what solid-state physicists call an 'indirect' band gap, meaning that any electron moving between the two energy states must change its momentum. This makes the transition less likely to occur.

Porous potential

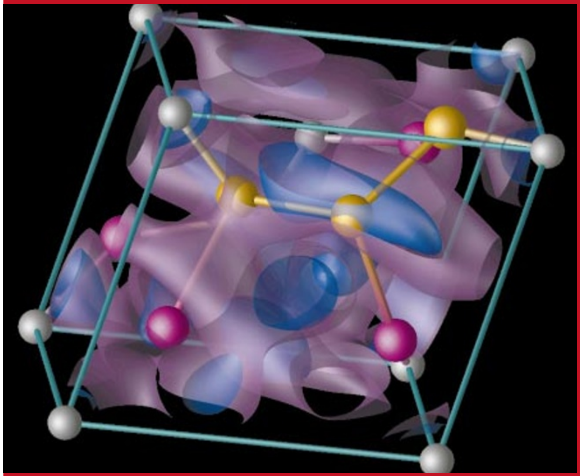
Despite these problems, researchers trying to persuade silicon to glow are currently in an upbeat mood. Silicon, they have found, does emit light if chopped down into tiny pieces just a few nanometres wide.

The first evidence for this remarkable change in silicon's behaviour emerged in 1990 from Canham's lab, then based at the Defence Research Agency (DERA's earlier incarnation) at Malvern in the English Midlands. Canham used hydrofluoric acid to dissolve silicon, etching away much of the material to leave a porous substance made up of a network of silicon 'nanowires'[1]. These tiny threads confine mobile electrons to narrow channels. As the space available to the electrons shrinks, quantum 'confinement' effects come into play. These affect the band gap, making it much easier for the electrons to move between energy states.

The benefits are impressive. Illuminate silicon nanowires with laser light to create pairs of negative and positive charge carriers and suddenly porous silicon glows with visible light. Known as photoluminescence, this process is 10,000 times more efficient in the nanowires than in normal silicon.

Ordinarily, silicon would emit infrared light, but Canham reasoned that the band gap is increased by the quantum confinement effect. As a result, the wavelength of the emitted light gets shorter as the nanowires get thinner. Because increasing the etching time produces narrower wires, the system can be tuned to produce light of different colours. Silicon that emits red, orange or yellow light is reasonably straightforward to make. After this, things get tricky because the tiny wires become increasingly fragile. But porous silicon that emits green and blue light has been reported[2].

Searching for silicon's perfect partner



This modelled blend of carbon, silicon and tin should emit light and match up with silicon's lattice spacing.

PEIHONG ZHANG/PENN STATE

As squeezing light out of silicon has tended to bring the words 'blood' and 'stone' to mind, physicists are always on the lookout for new ways to integrate optical devices with silicon chips. This search has led William Gillin of Queen Mary College in London down an unusual path — he has gone organic.

Gillin's organic (carbon-based) materials sit happily on a silicon surface because they are amorphous, rather than crystalline — there is no lattice mismatch because there is no crystal lattice. But the trick is to find such light-emitting substances that are sufficiently conducting to function in electronic devices. Gillin and his colleagues have created a silicon-based organic light-emitting diode (OLED) using a layer of erbium tris(8-hydroxyquinoline) deposited on another organic compound[9]. Positive charge carriers from a silicon substrate pass through the first organic layer to the erbium-containing layer, where they meet negative charge carriers provided by a top contact of aluminium. As the charge carriers recombine, they emit infrared radiation.

But these OLEDs have a long way to go before they are practical. The voltage needed to switch them on — 33 volts — is massive by industry standards, and their efficiency, just 0.01%, leaves a lot to be desired. Gillin is optimistic that it will be possible to get his devices to work at as little as 3 volts. They also have the advantage of being relatively easy to make and can emit light of different wavelengths if the erbium is replaced with different metals.

Other physicists are hoping to sidestep the problem of lattice mismatch by rational design. Rather than conducting trial-and-error searches for the right crystalline material to integrate with silicon circuits, they are using computational methods to devise semiconductors with the desired properties — both in terms of lattice constant and the band gap (see main text) needed to produce light of useful wavelengths.

John Joannopoulos and colleagues at the Massachusetts Institute of Technology have calculated that a specific blend of zinc, silicon, phosphorus and arsenic should have a lattice constant only 0.08% smaller than that of silicon[10], and should emit light at the ideal frequency for telecommunications. The only snag is that it is likely to be extremely hard to make.

Others have been searching for alloys that should be more amenable to synthesis. Vincent Crespi and his colleagues at Pennsylvania State University have teamed up with Arizona State University's John Kouvetakis, a materials scientist who specializes in synthesizing complex inorganic compounds. Crespi's team[11] has modelled blends of carbon, tin, germanium and silicon that have lattice constants within 1% of silicon's, and optimal wavelengths for fibre-optic transmission.

Kouvetakis is now trying to make these materials. So far, he has produced alloys of tin and germanium that are stable up to 400 °C and in which, crucially, the tin atoms seem to occupy the correct sites. Normally, tin separates out into clusters in these materials, destroying the crystal structure in the process. "The next challenge," says Crespi, "is to get the proper ratios of tin, silicon and germanium."

The prospects for silicon-based optoelectronic devices were boosted in 1996, when Philippe Fauchet of the University of Rochester in New York created a porous-silicon light-emitting diode (LED) integrated onto a chip[3]. LEDs are not bright enough for long-distance optical telecommunications, but they can be used for communicating over the short distances between and within chips. Before porous silicon came along, researchers trying to integrate LEDs into chips had been hampered by the same problems affecting lasers: the incompatibility of materials.

Fauchet's silicon-based LED is a proof of concept, but it is not yet technologically viable. The energy efficiency and switching speeds — the rate at which the LED can be turned on and off — still need to be improved. But progress is being made.

Nobuyoshi Koshida and his colleagues at the Tokyo University of Agriculture and Technology have greatly increased the efficiency of

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these LEDs. They used an oxidation reaction to eliminate much of the bulk-like 'non-confined' silicon that remains in the porous network — which otherwise transports most of the charge carriers[4]. Koshida's group has now raised the efficiency to about 1%, an improvement of five orders of magnitude over the earliest results. This is fine for display screens, says Canham. But to provide the photonic signals needed to transmit information between chips will require a further 10-fold increase. And switching speeds are still about two orders of magnitude too slow.

Dot comms

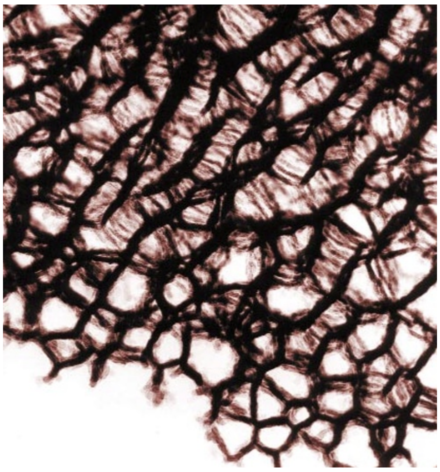
Using a network of silicon wires is not the only way to make the element glow. The same helpful quantum effects operate if the porous silicon is divided into nanometre-sized particles known as nanocrystals or 'quantum dots'. Last year, Munir Nayfeh of the University of Illinois at Urbana-Champaign and his colleagues used ultrasound to shatter porous silicon into nanocrystals. The smallest of these particles (about 1 nanometre across) emit blue light[5].

Other teams have reported similar successes. In February last year, Brian Korgel of the University of Texas at Austin and his colleagues described how to grow single nanowires that emit blue light[6]. Unlike porous silicon, which consists of a mesh of nanowires, Korgel's nanowires are discrete threads of silicon just 4–5 nm wide.

Lorenzo Pavesi of the University of Trento in Italy has used an alternative approach to create silicon nanocrystals. By firing high-energy silicon ions into quartz (silicon dioxide), and then heating the material to 1,100 °C, Pavesi and his colleagues generated silicon particles about 3 nm across that were embedded in the quartz. Last November, these researchers showed that not only do the nanocrystals emit red light when energized with a laser beam, but they can also amplify a 'probe' beam of the same wavelength as the emission[7]. Known as optical gain, this phenomenon is one of the fundamental features of laser emission.

Although the Italian team has taken the first steps towards creating a silicon laser, light amplification is not the same as laser action. In a laser beam the light is coherent: all the photons are in phase. To achieve this, emitted photons must stimulate the emission of others — the stimulated photons emerge in step with those that induced them. This 'stimulated emission' is achieved by placing the emitting material in an optical cavity bounded by mirrors which let photons bounce back and forth.

Tantalizingly, at the Materials Research Society meeting in Boston last December, Nayfeh reported optical gain and stimulated emission from his blue-light-emitting nanocrystals. Others in the field are now waiting for Nayfeh to publish quantitative data so that they can assess these claims.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Shining example: networks of porous silicon nanowires emit light in the visible spectrum.

But there might be another path to developing a silicon-based laser. When Ulf Gennser was working at the Paul Scherrer Institute in Villigen, Switzerland, he and his colleagues described a quantum-cascade laser (QCL) consisting of alternating layers of silicon and a germanium–silicon alloy[8]. These devices contain several five-layer blocks of light-emitting units, stacked one on top of the other. Electrons can 'tunnel' between individual layers, emitting a photon in the process.

Under the right conditions, this should lead to stimulated emission of coherent light, but the Swiss team has so far managed to produce only electroluminescence, not laser emission. "There remain many obstacles before we have a working laser," admits Gennser, who is now at the Laboratory of Microstructures and Microelectronics in Bagneux, part of the CNRS, France's national research agency. In addition, the device has to be cooled with liquid nitrogen. "I think the largest problem lies in achieving room-temperature operation," Gennser says. QCLs also emit too narrow a range of frequencies for use in long-distance optical telecommunications.

It remains unclear which approach will emerge as the best contender for lighting up silicon chips. But given the recent acceleration of progress, those intent on uniting the worlds of photonic and electronic information technology can afford to be optimistic. At the very least, silicon-based optoelectronics is starting to seem less of an oxymoron. ■

Philip Ball is a consultant editor of *Nature*.

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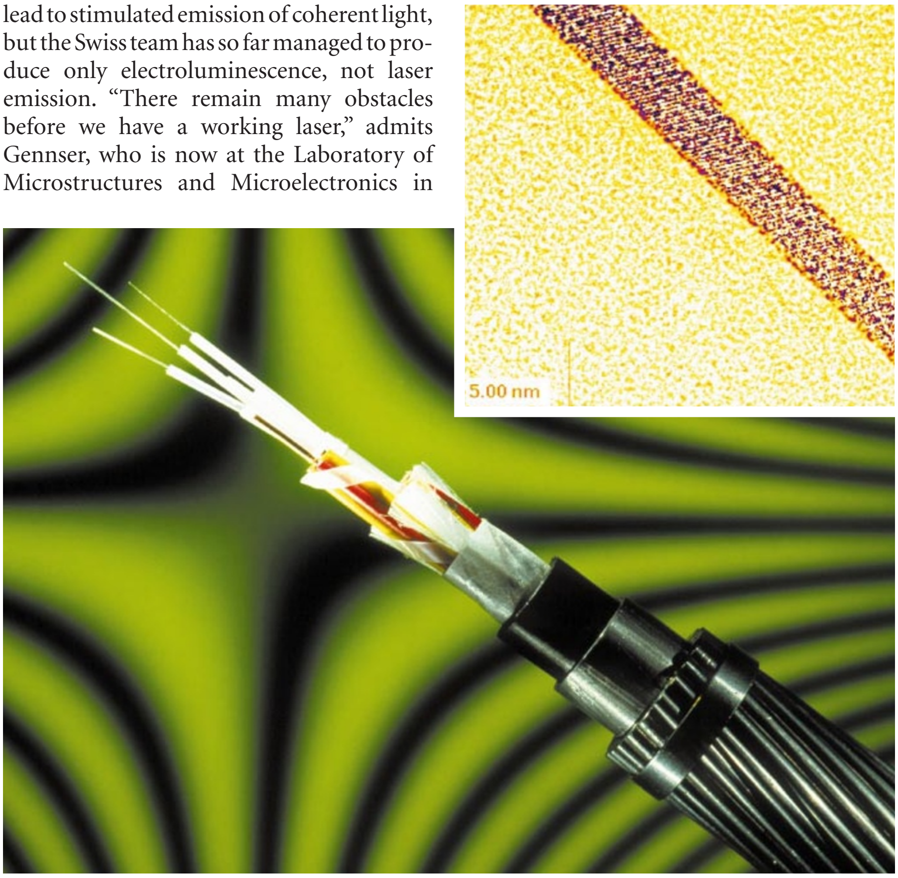

B. KORGEL

ALFRED PASIEKA/SPL

Light speed: single silicon nanowires (inset) might supply photonic signals to fibre-optic cables.