

thermodynamic stability of the co-continuous blends, by increasing flexibility at the interface between phases without requiring chain stretching.

The robustness of these co-continuous structures is borne out by the fact that they are not destroyed by crystallization, which has a much larger thermodynamic driving force but operates at a smaller lengthscale. The new polyethylene and polyamide blends created by Pernot and colleagues have enhanced properties, including lower creep and greater heat resistance. Co-continuous polymer blends containing as much as 80% polyethylene remain stable at much higher temperatures and have better mechanical properties than classical blends. For researchers interested in making both structural and functional polymers, these results point the way towards the design of stable co-continuous structures over a wide range of

compositions and polymer types.

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PHOTONIC MATERIALS

Teaching silicon new tricks

Atomic-scale engineering turns silicon into a material in which electronics and photonics can be merged, thus leading to microphotonic integrated circuits.

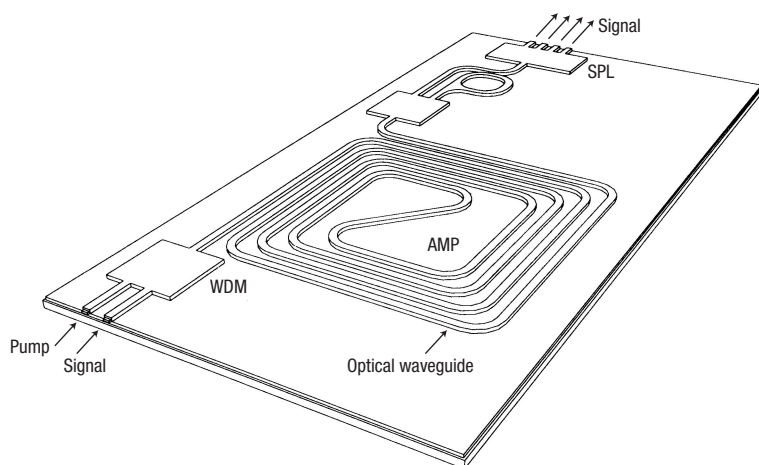
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Silicon is mostly known as the material from which electronic integrated circuits in computers are made. At a recent symposium* on 'Advances and future perspectives of silicon-based opto-electronics', it became clear that silicon can also play an important role in photonics, the technology in which information is transported and distributed by light.

Silicon has often been considered an impractical

material for photonic applications because it is an inefficient light emitter. But in a modern optical communications network, in which data is encoded and transported in streams of coloured bits of light, light must not only be generated, it must also be split, distributed, amplified, switched and detected. In fact, many of these functions can be carried out by silicon, and in many cases silicon has an advantage over other materials because of its superior electronic properties.

We already know that silicon is an ideal substrate for photonic integrated circuits in which several optical functions are combined on a single chip. The choice of the substrate material may sound trivial, but it is the substrate that determines what materials and structures can be grown or built on the circuit. For example, silica films of high optical transparency can be made by controlled oxidation of a silicon substrate (turning Si into SiO₂). In a microphotonic integrated circuit, tiny circuits of materials with different refractive indices are easily patterned on to the substrate by using photolithography and etching techniques that are well-established for



* European Materials Research Society Spring Meeting, Strasbourg, France, 18–21 June, 2001.

Figure 1 A glimpse into the future. A photonic integrated circuit made from silicon, in which optical waveguides, wavelength multiplexers (WDM), an amplifying loop section (AMP) doped with optically active erbium ions, and a 1 × 4 signal splitter (SPL) are integrated to form a miniature optical amplifier. Silicon nanocrystals that are incorporated inside the waveguide can serve as an antenna to excite the erbium ions more efficiently (Fig. 2).

silicon-based materials (Fig. 1).

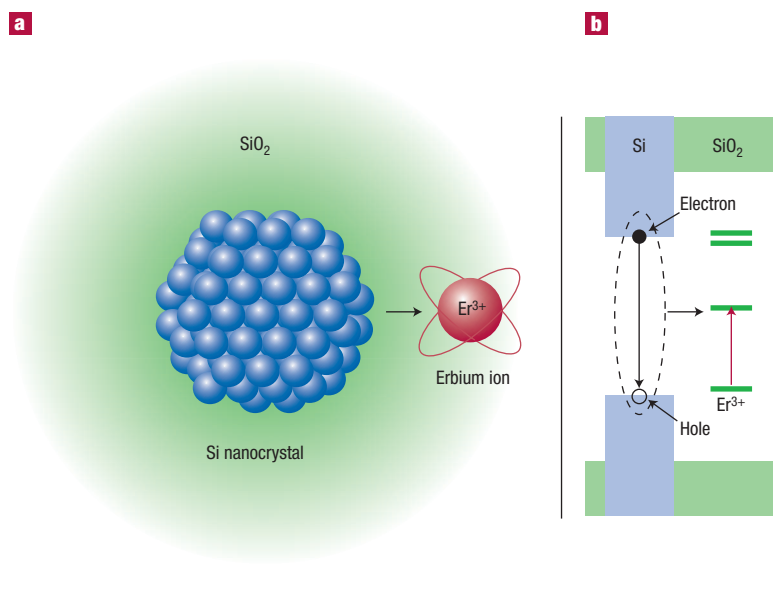
Silicon can also be used to guide light.

Crystalline silicon of high purity is completely transparent at the infrared wavelength (1.5 μm) that is the standard in telecommunications. Silicon is thus an ideal material to fabricate photonic crystals, a new class of materials that interact strongly with light¹. Such structures can be made by taking advantage of electrochemical etching processes in silicon (F. Müller, Max Planck Institute, Halle, Germany), or by using advanced etching and lithography techniques. Photonic crystals can be used to steer light in ways that are impossible with regular waveguides, or to suppress the spontaneous emission of light with undesired wavelengths. By infiltrating a photonic crystal with a liquid-crystalline polymer, of which the refractive index can be varied by an electric field, an electrically switchable silicon mirror can be made (P.M. Fauchet, University of Rochester, USA).

The semiconducting property of silicon can be used to develop a radically new concept for an optical amplifier. Amplification is essential in many photonic integrated circuits, and is often achieved by using optically active erbium ions that are dispersed in a SiO_2 waveguide. To achieve optical amplification, the erbium ions must be brought into an excited state. This can be done by using an external 'pump' laser. But because erbium ions do not efficiently absorb the pump light, an expensive high-power pump laser is required. This problem can be overcome by co-doping the erbium-doped SiO_2 waveguide with silicon nanocrystals that serve as an 'antenna' for the pump light². The silicon nanoparticles, composed of roughly 1,000 silicon atoms each, are 3 nanometres in diameter, and absorb light 10,000 times more efficiently than the erbium ions. Also, the nanocrystals absorb light in the visible range of the spectrum, for which inexpensive light sources are available.

The nanocrystal antenna effect is quite intriguing. It occurs because when a nanocrystal is excited, an electron-hole pair ('exciton') is formed inside the nanocrystal. Because the erbium ions are located within a few nanometres of the nanocrystal, the energy from the exciton can be subsequently transferred to the erbium ion (Fig. 2). This is a remarkably efficient process³. Many fundamental details of the energy transfer between nanocrystals and erbium have now become clear, which means that this concept can now be tested in optical amplifiers (D. Pacifici, Catania University, Italy).

Two years ago, research on silicon nanocrystals received a boost by the reported observation of net optical gain in SiO_2 waveguides doped with silicon nanocrystals⁴. Although many questions regarding this observation remain unanswered, the concept of efficient light emission from silicon nanostructures is still intriguing. Some argue that the light emission is caused by a 'classical' model of the recombination of quantum-confined excitons inside the nanocrystals (F. Huisken, Max Planck Institute, Göttingen, Germany). In contrast, the authors who originally reported the optical gain propose that the excitons would recombine at a $\text{Si}=\text{O}$ double bond at the interface between the silicon nanocrystals and the surrounding SiO_2 matrix (L. Dal Negro, University of Padova, Italy). If the latter model proves true, atomic-scale engineering of the $\text{Si}-\text{SiO}_2$



interface will be the key to achieving efficient light emission from silicon nanocrystals.

For many applications of silicon nanocrystals, large quantities of isolated, size-selected nanocrystals are required. They can be made by using pulsed-laser-induced pyrolysis of SiH_4 in a gas flow reactor (F. Huisken, Max Planck Institute, Göttingen, Germany), resulting in emission quantum efficiencies — which measure the number of photons emitted per absorbed photon — as high as 100%. Interestingly, the linewidth of the emission of individual nanoparticles can be as large as 120 millielectron volts (J. Linnros, Royal Institute of Technology, Sweden), the origin of which is unclear. This is a surprising result, because in the classical picture of emission from excitons that are confined in a nanocrystal, the expected linewidth is more than an order of magnitude lower. This once again demonstrates that models for light emission from silicon nanostructures are far from complete.

As a light source, silicon nanocrystals have an advantage over bulk silicon in that the electrical carriers are confined in a region in which no defects are present. This is because the SiO_2 matrix provides perfect passivation of the surface of these particles. However, the insulating effect of SiO_2 makes it difficult to inject electrical current into Si nanocrystals, and thus efficient light-emitting diodes are troublesome to make. Also, when large currents are passed through an oxide film it will eventually fail, resulting in a short circuit. Recent advances in using silicon-rich SiO_2 rather than pure SiO_2 as a host material indicate that more progress can be expected (S. Coffa, ST Microelectronics, Catania, Italy).

But bulk silicon should not yet be ruled out. A breakthrough was achieved recently⁵ by the group that holds the efficiency record for silicon solar cells (M. A. Green, University of New South Wales, Australia). Solar cells are optimized for the conversion of light into electricity, but it was found that similar devices are also very efficient for the reverse process.

Figure 2 Silicon nanocrystals as an antenna for erbium.

a, The wavefunction of an electron-hole pair ('exciton') in a silicon nanocrystal can couple to a nearby Er^{3+} ion in the silica matrix. **b**, Energy bands are shown for silicon nanocrystals and erbium ions embedded in a SiO_2 matrix. An optically excited electron-hole pair in the nanocrystal can recombine by transferring energy to an Er^{3+} ion. The latter is then excited from the ground state to the first excited state as indicated by the red arrow. Here atomic-scale engineering in combination with nanoscale energy transfer can lead to the development of a new class of miniature optical amplifiers (Fig. 1).

In these silicon light-emitting diodes, ultra-pure silicon was used with a geometrical surface texture that enhances the output coupling, bringing light-emission efficiencies for the ultra-pure silicon into the 1–10% range, some 1,000 to 10,000 times better than standard bulk silicon.

In general, the symposium demonstrated that silicon is becoming a key material for the fabrication of microphotonic integrated circuits: as a substrate, a photonic crystal, a light switch, an optical amplifier or

even a light source. The challenge now is to integrate these separate functions into true photonic integrated circuits.

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BIOSENSORS

Barcoded molecules

For a quarter of a century, barcodes have been used in the macroscopic world to tag goods in supermarkets. Can the same idea be used to track molecules in microbiology?

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A major goal of modern microbiology is the efficient detection of molecular binding events, such as the binding (hybridization) between two strands of DNA. Many other kinds of molecules, including antibodies, enzymes or proteins, can be identified by specific binding reactions. But when there are many different events occurring in a single sample, distinguishing between them becomes crucial. In this issue, Cunin *et al.*¹ report a new method of 'barcoding' mobile probe molecules, which can then be detected quickly and easily when they bind to the correct target.

Most detection strategies begin with probe molecules of known structure immobilized on a solid substrate, for example a glass slide. To detect binding reactions between these probes and target molecules present in the analyte (usually a solution), the targets must be labelled. Many labelling techniques now exist: the most popular requires fluorescent molecules to be attached to the target. After rinsing away unbound target molecules from the glass slide, successful binding is detected by fluorescence from the bound target when illuminated by light at the correct wavelength.

In practice, several hundred biomolecules are expressed at different levels in a living cell, so usually more than one molecule is of interest, and an array of different probe molecules must be patterned onto the slide². The chemical identity of the target molecule bound to the probe molecule is therefore encoded as an *x,y* position on the slide (Fig. 1a). The main drawback in using a flat substrate for immobilization is that any target molecule in the analyte has to pass many different sites to bind to its matching probe. Even if the analyte volume is as low as a single drop,

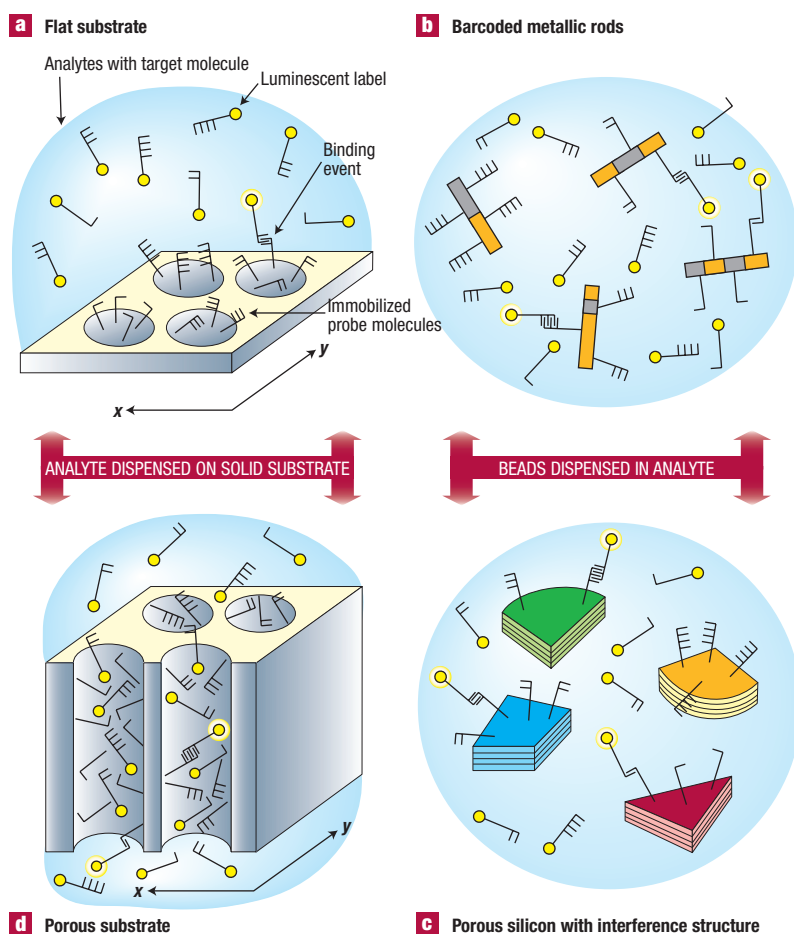


Figure 1 Probes for tracking biomolecular binding events can be identified by **a**, an *x,y* position on a flat substrate; **b**, using barcoded metallic rods; **c**, the interference colour of porous silicon fragments; or **d**, an *x,y* position in a porous substrate.