active sites are designed for electrostatic stabilization of ionic transition states by solvating these states to a greater extent than water can[8].

At the time that Watson and Crick proposed their disfavoured tautomer model there were no known structures for base mispairs. Since then, NMR, X-ray and enzyme kinetic studies have revealed the presence of 'stable' mispairs consisting of ionized and wobble structures in favoured tautomeric states. So the ball is now in the other court — it is the mutagenic relevance of disfavoured tautomers that is now in question. Are ionized and protonated base pairs sufficiently stable to 'short-circuit' the utilization of disfavoured tautomers in the polymerase active site? The study by Zewail and coworkers may open a window to address this issue. □

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OPTOELECTRONICS

Silicon sees the light

David A. B. Miller

SILICON may sparkle in the eyes of the electronics community, but to those in optics it has remained a depressingly dull grey. It emits light very feebly, and its ability to control photons is similarly dim. Lu and colleagues, on page 258 of this issue[1], show that growing very thin, alternating layers of silicon and silicon dioxide may change all that. They see strong evidence that the quantum confinement that can occur in such 'superlattice' structures may allow us to turn silicon into a shining example of an optoelectronic material. Their superlattice can emit light (luminesce) with a colour that can be controlled by the choice of silicon layer thickness.

Optoelectronics is becoming increasingly important for handling information. Long-distance telecommunications are now dominated by optical fibres. Semiconductor lasers are key to compact discs for information storage. Lasers and light-emitting diodes are used in many printers, and in display devices such as liquid crystal panels and indicator lights.

With the notable exception of various kinds of silicon photodetectors, most semiconductor optoelectronic devices are made from compounds of group III and group V elements, such as gallium arsenide. These compounds dominate semiconductor optoelectronics because of the 'direct bandgap' of many III–V materials: their electronic structure is such that an electron can be boosted directly from the valence to the conduction band by absorption of a photon. Direct bandgaps result in strong optical absorption and efficient light emission; they permit the manufacture of compact high-speed photodetectors, bright light-emitting diodes, lasers and very effective optical modulators. Silicon, however, has an 'indirect bandgap' — a phonon (crystal vibration) is needed to complete the all-important optical transition involved in light absorption or emission, fatally weakening this optical transition for many applications.

When semiconductor structures are made in sizes of about 1–10 nm, the electrons become quantum-confined. The conduction electrons in semiconductors (and their positively charged analogues, the 'holes' in the valence band) are not only particles but quantum mechanical waves, so, when they are confined to a small region, the only allowed energies of electrons and holes are those corresponding to the standing wave patterns that will fit in this region. This confinement therefore allows some tuning of the allowed energy levels, and under some circumstances could change the bandgap of a material from indirect to direct.

Interest in the possibility of light emission from silicon got a boost a few years ago with the observation that a form known as 'porous silicon' luminesced brightly[2]. The mechanism for this bright emission is still controversial[3]; although the structures are small, the emission wavelength does not show the dependence on size expected from quantum confinement. In contrast, the results obtained by Lu and colleagues[1] show size dependence very characteristic of quantum confinement.

Quantum confinement is already routinely used in III–V optoelectronics. Thin 'quantum well' layers give improved laser efficiencies and particularly effective optical modulators. Such quantum well or superlattice techniques have also been explored in silicon–germanium multilayered structures. Recently, for example, with additional quantum confinement from etching the layers into small posts (or 'quantum dots'), efficient, electrically driven light-emitting diodes have been demonstrated in silicon–germanium superlattices[4]. The approach of Lu and colleagues is different again, not only in its use of silicon dioxide, but also because the materials are not crystalline. The quality of their growth may be particularly crucial in making such amorphous materials luminesce efficiently.

Why try to make a better silicon-based optoelectronic material? There may be some naivety in the community about the impact such a material would have, perhaps just as naive as the predictions made some years ago that III–V electronic devices might displace silicon electronics. III–V optoelectronics works well, can be low-cost and has a growing weight of technology behind it. Nonetheless, other options are always welcome, and the massive investment in the silicon industry could help a silicon-based technology. The choice by Lu and colleagues to work with silicon and silicon dioxide is particularly canny — this system must be one of the most investigated because of its central role in silicon electronics.

There is also the motivation of making optoelectronics work better with silicon electronics. As silicon electronics becomes ever more impressive (roughly doubling the number of transistors on a chip every 18 months, for example), the usual electrical interconnection technology of metal wires has a harder and harder job to send information within machines. Optical systems are already being used to replace long electrical cables and can also avoid many of the problems that plague wired connections at shorter distances (such as high power dissipation and limited bandwidth). The ability to integrate high-performance optoelectronics with silicon may be crucial in taking full advantage of the features offered by optical links. Growing III–V devices on silicon has proved difficult, but hybrid integration techniques are emerging, with thousands of III–V optoelectronic components successfully bonded to silicon circuits[5]. Silicon-based devices grown directly on silicon electronics could prove an attractive option.

There is, of course, much work to be done, and researchers into III–V optoelectronics can still sleep at night for some time to come. Nevertheless, the work of Lu and colleagues is an important demonstration of the potentially useful properties of these silicon-based structures. Many stages remain before we can seriously start to assess device possibilities (including, for example, electrically pumped light emission), but their work will surely stimulate more activity in this field and may yet give silicon an even brighter future. □

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