formation of hydroxylamine from ammonia and air (Fig. 1c). Reaction of hydroxylamine with cyclohexanone produces the cyclohexanone oxime, which is then converted to CPL in a rearrangement catalysed by the acid sites in the AlPO. The open structure of the catalyst (with 7.3-Å pores) allows reactants, intermediates and products to interact freely with each other and with the active sites of the catalysts. The whole reaction takes place at only 80 °C. The selectivity for CPL is respectable — up to 78% using an AlPO catalyst doped with manganese and magnesium. Such yields are still too low for a commercial process, which would require selectivity of 95% or more. But there is no reason why the selectivity should not be increased by systematically determining the most efficient catalysts to use.

The work represents real innovation in a well-studied reaction, and opens up the possibility of applying a similar approach to many other reactions, such as epoxidation (used, for example, to produce epoxy resins and many other products). At the same time, it highlights the intellectual challenge of developing cleaner, greener chemical processes[6]. We must hope that other chemists will be inspired to rise to that challenge.

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SOLID-STATE PHYSICS

Silicon's new shine

Gareth Parry

The semiconductor material used in computing systems does not emit light. But a silicon-based structure that can modulate light from an independent source might aid the marriage of optical and electronic components.

Electronic components made of silicon have so far coped with almost every new challenge in the processing and storage of data. But substantial further progress might only be possible if optical (light-based) technology is used to help distribute or communicate information within, or possibly between, processors[1,2]. On page 1334 of this issue[3], Kuo and colleagues report the first observation in a germanium–silicon semiconductor structure of an optical effect — the quantum-confined Stark effect. Their find could lead to the fabrication of silicon-based integrated circuits containing both electronic and optical components.

The optical telecommunications networks that span the globe cope with separated electronic and optical technologies. But within a compact processing or computing system, the benefits of monolithic integration — reduced cost, improved reliability and simpler packaging — are more salient. Attempts to use optical and electronic parts together in such a system, however, have always run into the problem that light-emitting optical components are made from compound semiconductors that have a very different crystal structure from the silicon so successfully used for semiconductor electronics — making integration of the two difficult.

Although silicon can absorb light, and convert it into an electrical signal, it does not itself easily give out light — unlike some other semiconductor crystals that can be used to construct lasers. Silicon belongs to a class of semiconductors known as indirect-band-gap semiconductors. In such materials, light-emitting transitions between electrons in the high-energy conduction band states (which can move around the crystal and contribute to electronic conduction) and those in the lower-energy valence band states (which are localized to a particular atom) are not allowed. Over the years, attempts to get around this problem have met with little real success, and interest has shifted from the possibilities offered by silicon-based lasers to those of silicon-based optical modulators[2].

A modulator is analogous to a camera shutter: it transmits light when it is open, but absorbs light when it is closed. Depending on the voltage applied by the neighbouring electronic components, the modulator will either transmit or absorb a remotely generated, continuous laser beam that is directed on to it. This method of controlling light output is just as good as if the modulating material produced the light itself. The best optical modulators are based on compound semiconductor materials that use the quantum-confined Stark effect[4], in which the allowed energy levels of electrons in very thin layers (typically 10 nanometres) change when an electric field is applied. These modulators can operate at low voltages and can be switched from an 'on' to an 'off' state at even higher frequencies than is possible using lasers.

Kuo *et al.*[3] observe, for the first time, the quantum-confined Stark effect in crystalline germanium layers grown on silicon wafers. Unlike compound semiconductors, germanium (Ge) and its alloy silicon–germanium (SiGe) are perfectly acceptable materials for use in silicon electronics, as they have a similar crystal structure to that of silicon. The layers of Ge used by Kuo *et al.* are 10 nanometres thick, and ten of these are separated by SiGe layers, each 16 nanometres thick. These SiGe separating layers form a barrier to electrons and confine them in the thin layers of Ge. As a result, the energy levels of these electrons differ from the energy levels of the electrons found in the bulk crystal; the exact energy levels can be calculated quantum mechanically taking into account the shape of the well.

The thicknesses of the layers are chosen so that, when no voltage is applied, incident photons do not have sufficient energy to be absorbed (for that to happen, they would need enough energy to kick an electron in the structure into the next quantum-mechanically allowed energy level). But when a voltage is applied, the electric field changes the shape of the energy well, and the allowed energy levels of the electrons change sufficiently that the incident photons can be absorbed. Thus Ge–SiGe absorbs or transmits light according to an electronic signal from neighbouring electronic components — it acts as a modulator.

Although understood and used for 20 years in compound semiconductors for optical communication purposes[4], this effect was not expected to be found in Ge–SiGe. This is because germanium, like silicon, is an indirect band-gap material. The ingenious technique reported in Kuo and colleagues' paper[3] involves absorbing photons to higher energy levels in the conduction band of the germanium quantum wells. This takes advantage of the fact that transitions between those selected energy levels — unlike those between the lowest conduction and valence bands — are allowed. The effect that the authors observe is as strong as that seen in compound semiconductors.

Further developments must occur before we see a fully integrated silicon optoelectronic circuit. For example, most silicon electronic circuits are produced by the deposition of various oxide and metallic layers, whereas the structures used by Kuo *et al.* are produced by crystal growth. The authors are confident that their different fabrication process is suitable for mass production. Let's hope they are right.

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