PHOTOVOLTAICS

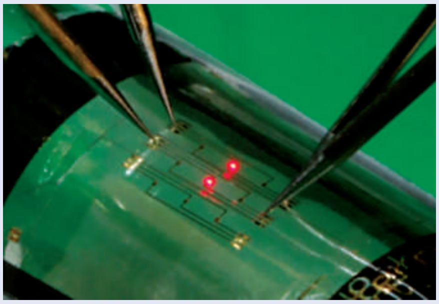
Flexible optoelectronics

It is widely believed that the fabrication of foldable and bendable optoelectronics requires technologies such as organic polymer semiconductors or colloidal quantum dots, both of which can be deposited onto plastic substrates using solution-processing techniques.

It now turns out that foldable optoelectronics can also be made from conventional inorganic semiconductors such as GaAs and InP, thanks to a new innovative fabrication approach developed by John Rogers and co-workers at the University of Illinois at Urbana–Champaign and Northwestern University in the USA (*Adv. Mater.* doi:10.1002/adma.201000591; 2010). Until recently, the deposition of such compound semiconductors onto a plastic substrate was thought to be impossible owing to their incompatibility with semiconductor fabrication technologies such as molecular beam epitaxy and metal organic chemical vapour deposition.

The researchers used an etch-and-release scheme to fabricate red (~675 nm) LEDs based on conventional GaAs–InGaP semiconductors on a thin sacrificial layer of AlGaAs deposited on a GaAs wafer. The clever part of the scheme is that the sacrificial AlGaAs layer can be etched away after fabrication, which allows the active semiconductor forming the LED to be transferred onto a thin plastic substrate. The researchers say that their approach produces brighter and more efficient LEDs than organic light emitters, while still enjoying the benefits of a flexible plastic substrate. A rather unexpected outcome is the extreme flexibility of the LEDs, which allegedly permits a bending radius as small as 0.7 mm — appreciably lower than the previous record of several millimetres using organic LED technology.

Fabrication of the device starts with the growth of microscale LEDs, each measuring 100 μm × 100 μm × 2.523 μm, using the etch-and-release scheme. The LEDs are then removed and transfer-printed as arrays onto a substrate of polyethylene terephthalate coated with polyurethane. An epoxy coating is applied, etching is performed and ohmic metals are then deposited to define the n- and p-electrodes of the microscale LEDs. Electrical interconnection lines are formed through photolithographic patterning.



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The final encapsulation process involves applying epoxy of varying thickness to different regions. The thickness of the encapsulation layer is incremented in steps during deposition to reduce the mechanical strain on the LED quantum wells when the substrate is folded or flexed.

It is suggested that the development of these highly flexible LED arrays, which have superior optical performance and mechanical properties to organic LEDs, may prove useful for creating flexible display technologies.

SONIA SHAHI

SILICON PHOTONICS

Nonlinear optics in the mid-infrared

Carefully designed nanophotonic silicon waveguides, when pumped at long wavelengths to avoid inherent losses, are opening the door to useful nonlinear processes in the mid-infrared.

Bahram Jalali

Silicon photonics is now a thriving community and a blossoming business thanks to its compatibility with the manufacturing infrastructure of silicon electronics. Owing to the loss characteristics of optical fibre, today's data interconnects exploit the near-infrared (IR) region of the electromagnetic spectrum at around 1,550 nm, where fibre losses are lowest (0.1–0.2 dB km^{-1}). However, silicon still suffers from an inherent problem at these wavelengths: a strong loss mechanism that 'kicks in' under high-power pumping. This tendency of silicon to become lossy at high intensities in the near-IR has been the major hurdle in creating practical optical amplifiers and wavelength converters — fundamental building blocks of data communication networks — in silicon photonics, as such devices require powerful pump sources to operate.

Although silicon is normally transparent and thus exhibits low propagation losses at near-IR wavelengths, at high intensities it begins to absorb light because of two-photon absorption (TPA), in which two photons can 'cooperate' to excite an electron out of the valence band and into the conduction band (Fig. 1). TPA creates a population of free carriers that can also absorb light through free-carrier absorption[1–3]. As silicon has an indirect electronic band structure, its intrinsic recombination rate of free carriers is low — only 10^3–10^6 per second (depending on its purity) — compared with approximately 10^9 per second in direct-band structure semiconductors such as GaAs. Consequently, the free-carrier population quickly builds up at high light intensities, resulting in significant optical loss.

This problem dramatically reduces when the wavelength of the incident light exceeds ~2,200 nm (refs 4,5), which is the threshold for TPA to occur (Fig. 1) and is around half the bandgap energy of silicon. As a result, the mid-IR range has been hailed as a promising future regime for silicon photonics, particularly for building nonlinear optical devices that operate at high power[6–9]. Now, two exciting independent reports in this issue of *Nature Photonics* reveal this potential by demonstrating high-performance parametric amplification and parametric generation of mid-IR light in silicon waveguides[10,11]. Both groups report the use of four-wave mixing (FWM) using the Kerr nonlinearity in impressively compact nanophotonic waveguides. In contrast with previous studies, which generated 2 μm light through FWM in silicon by pumping it at ~1,550 nm, these new demonstrations pump near the two-photon bandedge of 2,200 nm, where TPA, and therefore also free-carrier absorption, is far less.

Silicon has several additional attractive properties that make it an excellent nonlinear optical crystal in the mid-IR range, including a large thermal conductivity and a high-optical-damage threshold[7,8]. Mid-IR sources based on silicon could potentially be used in medicine for ablating tissue by targeting resonant absorption peaks in water, amide bonds in collagen and other tissue chromophors[7,8,12]. There are also potential industrial applications, such as the detection of hydrocarbon emissions from vehicles, factories and oil fields, as well as for remote chemical and biological sensing. However, there is currently a shortage of compact and low-cost mid-IR sources, primarily because conventional semiconductor diode laser technology — the staple for optical communication and storage applications — does not scale well to longer mid-IR wavelengths. This inability is due to the lack of semiconductors with sufficient bandgap, and also because a diode's leakage current increases exponentially as its bandgap is reduced.

In a significant step forward for mid-IR silicon photonic technology, William Green and co-workers from IBM and Columbia University report parametric amplification at 2,200 nm in silicon nanophotonic waveguides, with gains as high as 25 dB (ref. 10). Their waveguides, which had lengths of 4 mm and impressively small effective areas of 0.3 μm², were pumped near the two-photon bandedge of 2,200 nm using a Ti:Sapphire optical parametric oscillator at a repetition rate of 76 MHz and with pulses of width 2 ps. The gain was sufficient to overcome the fibre-to-fibre losses resulting from coupling and propagation in the waveguide, achieving a considerable net amplification of 13 dB.

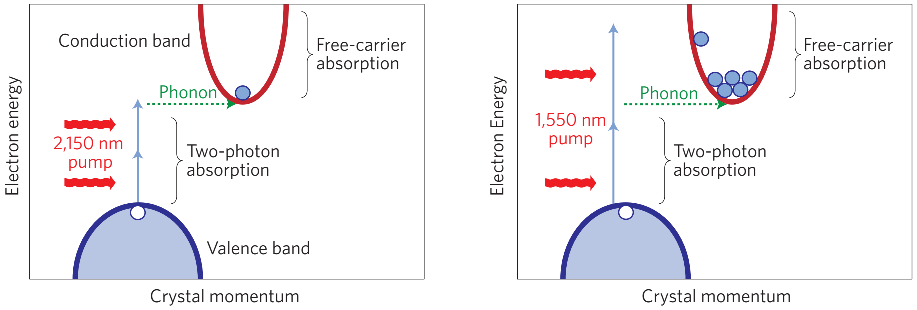

Figure 1 | Comparison of two-photon absorption leading to the generation of free carriers for mid-IR (left) and near-IR (right) pumps. Free carriers accumulate rapidly after creation because of their relatively long lifetime in indirect-bandgap silicon, causing pump and signal photons to be lost through free-carrier absorption. The rate of two-photon generation depends on the density of electron states in both the valence band (initial state) and conduction band (final state). The density of states vanishes below the bandgap and increases with energy. Hence the generation rate is much larger for higher-energy pump photons (left) than those at the bandedge (right) because of the larger number of available states. Two-photon absorption can also occur from initial states that are lower in the valence band (not shown).

Also in this issue[11], Sanja Zlatanovic and colleagues from the University of California at San Diego and the Center for Research and Education in Optics and Lasers in the USA report parametric generation of mid-IR light up to 2,388 nm in waveguides of length 3.8 mm and effective area 0.35 μm² — dimensions similar to the waveguides of Green and co-workers. However, unlike the work of Green and colleagues, Zlatanovic and colleagues used compact fibre-based sources for the pump and probe in their experiments. Using first-order FWM conversion, the group was able to reach a maximum wavelength of 2,388 nm using a probe at 1,758 nm and a pump at 2,025 nm, with a conversion efficiency of −36.8 dB. The pump and probe beams (1 ns pulses at 1 MHz) were generated by two independent degenerate parametric mixers that used a seed at 1,300 nm and a tunable pump at 1,589 nm in an 8-m-long highly nonlinear fibre. A nonlinear parameter of $n_2 = 10.8 \times 10^{-18}$ m² W^{-1} was estimated, which is consistent with known values for the Kerr coefficient in silicon. The use of a telecommunications-wavelength laser and fibre technology to generate the pump and probe beams is a new and promising approach to addressing the need for low-cost and compact sources of mid-IR light.

Although optical amplification and wavelength conversion through mid-IR pumping have both already been demonstrated through stimulated Raman scattering in the mid-[13] and near-IR[14], the gain bandwidth of stimulated Raman scattering in silicon is narrow at ~1 nm, although it can be somewhat broadened with multiwavelength pumping. In contrast, the FWM approach provides amplification and wavelength conversion over a larger bandwidth as long as phase matching is maintained[15–18] (a constraint not required by stimulated Raman scattering). Phase matching for FWM can be achieved through dispersion engineering with careful design and very precise control of the waveguide's cross-sectional dimensions. In this way it is possible to design waveguides with nearly zero dispersion over appreciable optical bandwidths.

In addition to phase matching, efficient nonlinear parametric effects also require low losses and a large Kerr nonlinear coefficient. The high optical intensities resulting from tight optical confinement in the high-index-contrast silicon-on-insulator (Si/SiO$_2$) waveguide of Zlatanovic *et al.* produce a surprisingly high effective nonlinearity of $\gamma = 110$ W^{-1} m^{-1} at ~2,200 nm (ref. 11). Because high intensities also lead to TPA, a possible figure of merit that takes these two counteracting effects (as well as the wavelength dependence) into consideration is $n_2/\beta_{\mathrm{TPA}}\lambda$, where n_2 is the component of the refractive index caused by the Kerr nonlinearity, β_{TPA} is the TPA coefficient and λ is the pumping wavelength. The reduction in TPA at the two-photon bandedge of 2,200 nm gives a figure of merit that is approximately an order of magnitude higher than at the telecommunications wavelength of 1,550 nm (ref. 11).

Although the demonstrations reported in this issue[10,11] show great promise for making silicon sources and amplifiers at mid-IR wavelengths, it should not be forgotten that the quantum cascade laser[19–21] represents another path for serving the mid-IR spectrum. There has also been rapid progress in fibre-based mid-IR amplifiers and lasers, as exemplified here by the use of fibre-based pump and probe sources in the work of Zlatanovic and co-workers[11].

It remains to be seen whether silicon mid-IR sources and amplifiers will become the solution of choice for future mid-IR photonics. However, what is clear is that the recent interest and activities in the mid-IR regime of silicon photonics represent significant progress, giving hope for on-chip applications. After all, for chip-to-chip and intrachip optical interconnects to be fully realized, it may be necessary to compensate for signal losses through on-chip amplification. An all-optical on-chip signal processing system may also find use in dispersion mitigation and signal conditioning in future fibre-optic networks. Another potential application is the development of mid-IR amplifiers and sources for biochemical sensing and medical therapy at wavelengths that are hard to reach through other means. For such applications, both FWM and Raman techniques should be considered, and in both cases pumping in the mid-IR is preferable. ❐

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References

1. Liang, T. K. & Tsang, H. K. *Appl. Phys. Lett.* **84,** 2745–2747 (2004).
2. Claps, R., Raghunathan, V., Dimitropoulos, D. & Jalali, B. *Opt. Express* **12,** 2774–2780 (2004).
3. Bristow, A. D., Rotenberg, N., van Driel, H. M. *Appl. Phys. Lett.* **90,** 191104 (2007).
4. Raghunathan, V., Shori, R., Stafsudd, O. & Jalali, B. *Phys. Stat. Sol. A* **203,** R38–R40 (2006).
5. Bristow, A. D., Rotenberg, N. & van Driel, H. M. *Appl. Phys. Lett.* **90,** 191104 (2007).
6. Soref, R. A., Emelett, S. J. & Buchwald, W. R. *J. Opt. A* **8,** 840–848 (2006).
7. Jalali, B. *et al. IEEE J. Sel. Top. Quant. Electron.* **12,** 1618–1627 (2006).
8. Jalali, B. & Fathpour, S. *J. Lightwave Technol.* **24,** 4600–4615 (2006).
9. Soref, R. *Proc. SPIE* **6898,** 689809 (2008).
10. Liu, X., Osgood, R. M. Jr, Vlasov, Y. A. & Green, W. M. J. *Nature Photon.* **4,** 557–560 (2010).
11. Zlatanovic, S. *et al. Nature Photon.* **4,** 561–564 (2010).
12. Ebrahim-Zadeh, M. & Sorokina, I. T. *Mid-Infrared Coherent Sources and Applications* 1st edn (Springer, 2007).
13. Raghunathan, V., Borlaug, D., Rice, R. & Jalali, B. *Opt. Express* **15,** 14355–14362 (2007).
14. Rong, H. *et al. Nature Photon.* **2,** 170–174 (2008).
15. Fukuda, H. *et al. Opt. Express* **13,** 4629–4637 (2005).
16. Espinola, R. L., Dadap, J. I., Osgood, R. M. Jr, McNab, S. J. & Vlasov, Y. A. *Opt. Express* **13,** 4341–4349 (2005).
17. Rong, H., Kuo, Y.-H., Liu, A., Paniccia, M. & Cohen, O. *Opt. Express* **14,** 1182–1188 (2006).
18. Foster, M. A. *et al. Nature* **441,** 960–963 (2006).
19. Faist, J. *et al. Science* **264,** 553–556 (1994).
20. Maulini, R. *et al. Appl. Phys. Lett.* **95,** 151112 (2009).
21. Slivken, S., Bai, Y., Gokden, B., Darvish, S. R. & Razeghi, M. *Proc. SPIE* **7608,** 76080B (2010).

QUANTUM OPTICS

A spooky light-emitting diode

The generation of entangled photon pairs is usually a complex process involving optically driven schemes and nonlinear optics. The recent demonstration of an electrically powered light-emitting diode that is capable of this task looks set to greatly simplify experiments in the field of quantum information processing.

Val Zwiller

The thought experiment suggested by Einstein, Podolsky and Rosen[1] in 1935 to test the locality of quantum mechanics was experimentally demonstrated decades later using pairs of entangled photons[2,3]. In recent years, quantum entanglement has become a crucial resource for quantum information processing, creating the need for an efficient and reliable source of entangled photon pairs on demand.

The generation of polarization-entangled photon pairs has traditionally been performed with lasers and nonlinear crystals, yielding Poissonian emission statistics. This Poissonian distribution makes it impossible to deterministically generate a single entangled photon pair on demand. Other weaknesses of this technique include its very low overall energy efficiency and high complexity. Now, reporting in *Nature*, Salter *et al.* describe a quantum-dot-based LED that could be an elegant electrically driven alternative[4].

In 2000, Benson *et al.*[5] suggested the idea of using a quantum dot to generate pairs of entangled photons on demand. By populating a single quantum dot with two electrons and two holes (known collectively as a biexciton), two photons can be emitted in a cascade with an exciton as the intermediate level. Provided that the two excitons are degenerate (that is, indistinguishable in energy) and thus yield no which-path information, the two photons that are emitted will be entangled in polarization. Implementing this scheme has proved challenging because the two exciton levels are usually non-degenerate in quantum dots. The problem was first solved by Akopian *et al.*[6], who observed polarization-entangled photon pairs by energy filtering between the two exciton energy levels. Using quantum dots with small exciton fine-structure splittings, the Shields group at Toshiba research labs in Cambridge, UK, was then able to demonstrate entangled photon pair generation without filtering between the two exciton levels[7].

These first experiments used a laser to excite the quantum dot. An alternative method would be to embed a quantum dot with a small enough fine-structure splitting in a p–n junction, thus yielding a compact LED capable of generating entangled photon pairs on demand with high power efficiency and sub-Poissonian statistics. Such an LED, now realized by Salter *et al.*, could replace complex experimental set-ups with a single compact electrically pumped device (Fig. 1). In the scheme of Salter *et al.*, self-assembled InAs quantum dots were grown by molecular beam epitaxy in a microcavity tuned to the InAs quantum dot emission at 1.4 eV (wavelength of ~890 nm) and doped to form a p-i-n (p-type/intrinsic/n-type layers) heterostructure centred on the quantum dots. Electrical contacts were placed on top of the device, with small windows allowing the emission from a single quantum dot to be observed.

The researchers revealed quantum entanglement in polarization by measuring cross-correlations between the biexciton and exciton emission as a function of polarization. The experiment was