Germanium and silicon photonics

Mike Cooke reports on recent research using germanium to enable infrared light-emitting devices to be created on silicon platforms.

In the past year or so, new optical communications technologies for data communications and high-speed computer processing have become available based on silicon (Si) waveguides [See Mike Cooke, Semiconductor Today, p80, September 2016]. Silicon provides a versatile platform for both optics and electronics, but suffers from major limitations in terms of generating light, which must either be supplied externally or created internally using III-V compound semiconductor materials.

Combining III–V materials with silicon is tricky, and germanium (Ge) is often used as a bridge. As a group IV material, Ge shares many chemical properties with Si and is already used in mainstream electronics production. Here we look at some ways for how Ge could help to make possible more integrated optoelectronics on a silicon platform.

Silicon germanium LEDs

China's Xiamen and Nankai universities have jointly developed lateral p-i-n SiGe/Ge/SiGe light-emitting diodes (LEDs) with high luminous extraction compared with a vertical design [Guangyang Lin et al, Appl. Phys. Lett., vol109, p141104, 2016].

An efficient Ge-based light-emitting device is highly desired as part of the drive to silicon-based optoelectronic integrated circuits. Since Ge has a narrower bandgap than Si (Table 1), generated light could be used in silicon photonic structures that require wavelengths longer than 1.1μm.

Table 1. Silicon versus germanium.

	Si	Ge
Bandgap	1.12eV	0.661eV
Wavelength	1.1μm	1.9μm
Separation at gamma point (k = 0, peak valence band)	3.4eV	0.8eV
Electron effective mass/vacuum mass	0.33	0.2
Hole effective mass/vacuum mass	0.5	0.3

The impediment to using Ge in this way is its indirect bandgap, which makes for very inefficient electron–hole recombination into photons. However, the difference between the indirect minimum and direct transitions between the conduction and valence bands is only about 140meV, giving a 'quasi-direct' gap. This difference can be further reduced by applying tensile strain.

On the processing side, Ge is already used in many mainstream electronics enhancements such as 'strained silicon' transistors and in SiGe bipolar transistors. This is in contrast to standard direct-bandgap light-emitting III–V compound semiconductors made of materials that poison the performance of standard Si components.

Some vertical LEDs using various SiGe combinations have been developed. The Xiamen/Nankai researchers believe that lateral junctions could be a better choice in terms of reducing carrier loss in defect-rich Ge buffer layers at the Ge/Si interface, light absorption in metal contacts, and self-absorption in Ge. "So far, few works were reported on Ge lateral junction light emission diodes, especially with lateral heterojunctions," they write.

The Xiamen/Nankai epitaxial structure was grown on a Ge 'virtual substrate' (VS) on silicon on insulator (SOI). Six 9nm Ge quantum wells were separated by 15nm $Si_{0.13}Ge_{0.87}$ barriers. The structure was annealed at 800ºC for 60 seconds, intermixing the 6x(SiGe/Ge) structure to give a uniform SiGe layer. Raman analysis suggests the resulting 159nm layer consisted of 95% Ge with ~1% strain. The strain in the underlying Ge was ~0.3%.

The researchers comment that the high annealing temperature of 800ºC enhanced the tensile strain due to differences in thermal expansion coefficients between Si and Ge. "The tensile-strained SiGe overlayer can also act as an external strain source leading to larger tensile strain in the Ge VS, which is beneficial for achievement of direct band luminescence from Ge," they add.

Fabrication (Figure 1) included dry etching down to the buried oxide insulator layer to give 10μm-wide waveguides, dry etching the SiGe layer to form a lateral double heterojunction (SiGe/Ge/SiGe), ion implantation to form p- and n-type SiGe contacts, doping activation

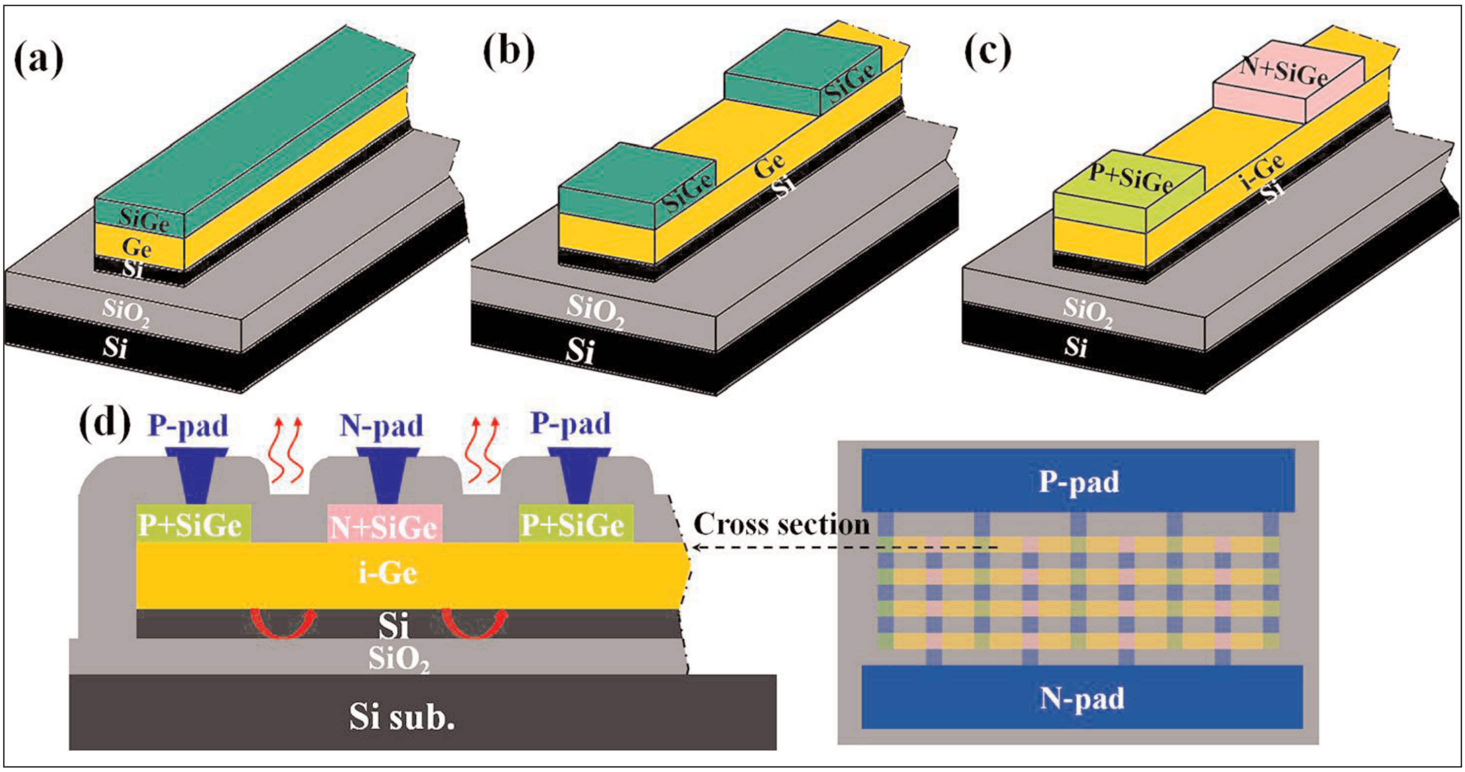

Figure 1. Fabrication flow of lateral p-SiGe/i-Ge/n-SiGe heterojunctions on SOI substrates: (a) SiGe/Ge/Si waveguides on SOI, (b) SiGe/Ge/SiGe lateral heterojunctions on waveguides, (c) selective ion implantation to form P^+ and N^+ SiGe regions, and (d) schematic of top view and cross sections.

at 650ºC for 15 seconds, encapsulation in silicon dioxide, formation of contact holes and deposition and patterning of aluminium electrodes and wiring. The team says that the fabrication process is CMOS-compatible, paving the way for integration with Ge MOSFETs.

Vertical p-i-n Ge homojunction devices were also fabricated on SOI with a similar area for comparison.

As current injection in the lateral device was increased, electroluminescence (EL) around 1600nm (1.6μm) wavelength was detected by an indium gallium arsenide (InGaAs) on indium phosphide (InP) photodetector (Figure 2). Red-shift was seen at higher currents due to Joule heating. At 2.5kA/cm^2 current injection, the peak intensity for the lateral heterostructure device was 4x that of the vertical homojunction structure. "In addition, the EL peak position of the lateral heterojunction locates at the higher energy side compared to the vertical homojunction, which might be attributed to modification of spectra by the cavity effect and/or weaker Joule heating effect," the researchers write.

The increase in intensity with current for 20μm- and 2μm-wide i-Ge region lateral devices is approximately quadratic (1.9 current-exponent for 20μm, 2.0 for 2μm), consistent with theoretical considerations of large carrier injection. The 20μm peak intensity is about 3x that of the 2μm device.

Light extraction from the device also benefits from reflection off of the silicon dioxide/silicon interface of the SOI substrate, giving enhancement from a cavity resonance effect.

First 1.3μm EL from MOCVD quantum dots

Japan's University of Tokyo claims "the first demonstration of EL at 1.3mm from InAs/GaAs quantum dots (QDs) monolithically grown on a Ge/Si substrate by metal organic chemical vapor deposition (MOCVD)" [Mohan Rajesh et al, Jpn. J. Appl. Phys., vol55, p100304, 2016].

The researchers see the room-temperature achievement as an important milestone towards the monolithic integration of QD lasers emitting at 1.3μm for silicon photonics application.

QD lasers can have improved characteristics such as low threshold current and high temperature stability compared with more traditional devices based on quantum wells. Producing electrically pumped lasers on silicon could plug the light generation gap in silicon photonics technologies. QD lasers have been produced through molecular beam epitaxy (MBE) on silicon, but MOCVD is often a preferred mass-production technology in terms of high throughput and low maintenance cost.

The Tokyo InAs in GaAs matrix QD structures were produced on a Ge interlayer on the Si substrate. III–V material such as GaAs tends to suffer from crystal imperfection when grown directly on silicon due to a large 4.1% lattice mismatch. Germanium has a smaller mismatch with GaAs of the order of 0.07%. Also, the thermal expansion coefficients of Ge and GaAs are similar, which is an important factor when high-temperature growth processes are used.

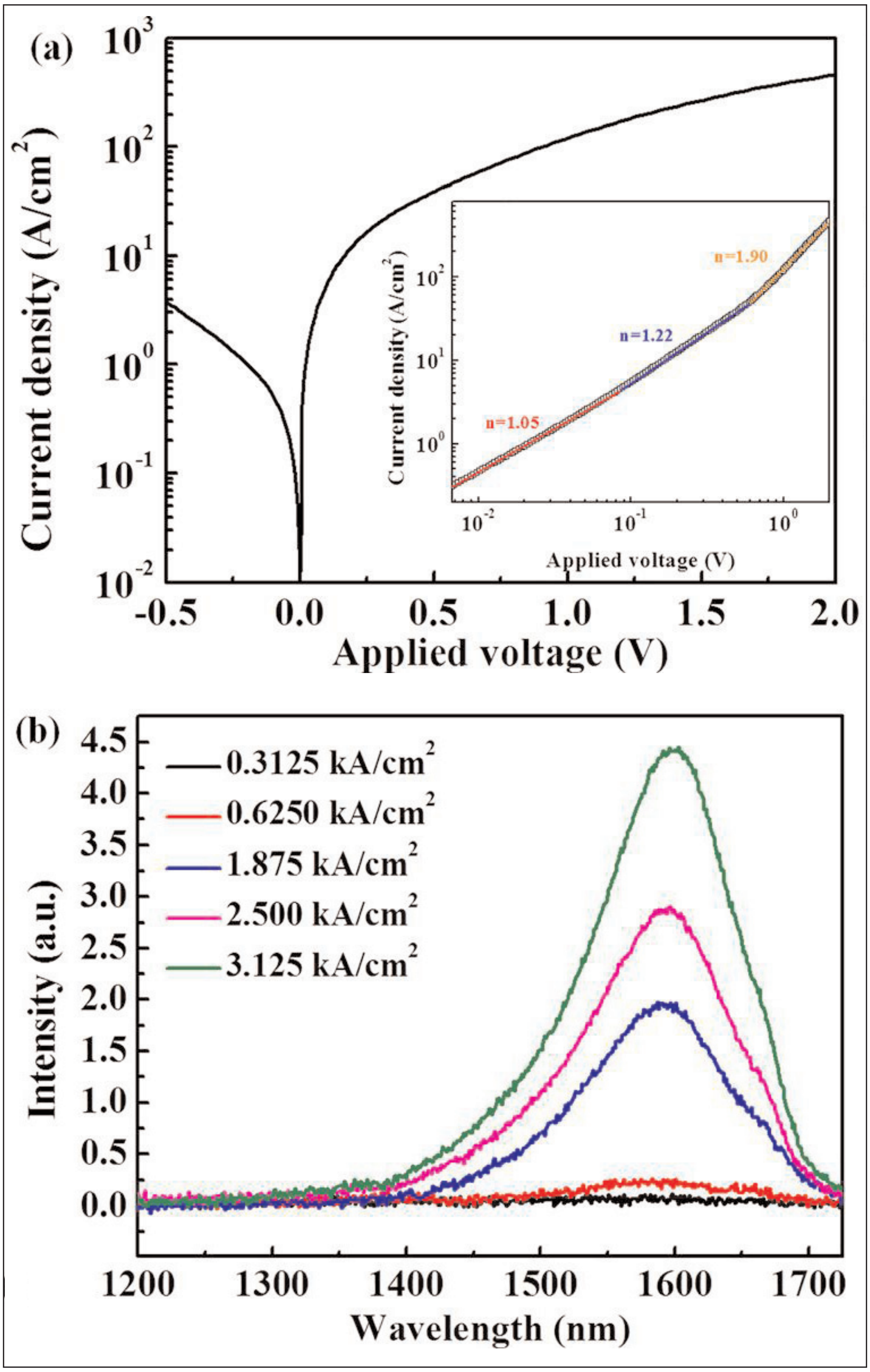

Figure 2. (a) Typical current density-voltage characteristic of heterojunction diode. Inset forward bias curve in log–log scale marked with extracted ideality factors; (b) EL spectra under various injection current densities.

The 2µm Ge interlayer was grown using ultra-high-vacuum CVD on a 6º-offcut silicon substrate. A further 100nm of Ge was grown after 5 minutes of cyclic annealing at 850ºC. The Ge/Si wafer was prepared for III–V MOCVD by a series of treatments to remove contaminants and native oxide.

When the Ge/Si wafer was loaded into the MOCVD reactor a further treatment of thermal annealing in tertiarybutylarsine at 650ºC for 10 minutes was used to desorb native oxide and create double atomic steps on the substrate surface, avoiding antiphase domains (APDs) in the subsequent growth.

The GaAs buffer layer consisted of 10nm nucleation on the As prelayer at 420ºC, 250nm low-temperature 500ºC material, and finally the main part at 650ºC to give 1.3µm or 3µm total thickness. The lower-temperature layers used triethylgallium precursor, while the high-temperature final part used trimethylgallium. Before QD deposition, the GaAs/Ge/Si wafer was annealed in tertiarybutylarsine.

The QDs were grown in a series of layers using antimony (Sb) as a surfactant. The Sb was irradiated onto the GaAs surface, after which the 3.8-monolayer InAs QD material was deposited at 495ºC. The growth was then interrupted for 80 seconds to allow the dots to form. The QD density was greater than $4.3 \times 10^{10}/cm^2$. The base width and height were 36nm and 7nm, respectively. "The density of QDs grown on GaAs/Ge/Si substrate is almost comparable to that of QDs grown on a GaAs substrate, used for the fabrication of low-threshold-current lasers," the team writes.

The QD layer was capped with 500ºC 7nm $In_{0.05}Ga_{0.95}As$ and 5nm GaAs. The purpose of the $In_{0.05}Ga_{0.95}As$ layer was to reduce strain and to red-shift the InAs QD emission wavelength to 1.3µm and longer with a full-width at half-maximum (FWHM) of ~44meV. The QD layers were completed with 600ºC 30nm GaAs spacer for the next QD layer.

The antimony (Sb) surfactant-mediated growth increases dot density and suppresses coalescence. With certain growth conditions it can also increase photoluminescence (PL) intensity. Previous work on InAs/GaAs QD MOCVD on Ge substrates has resulted in low densities and coalescence of dots.

It was found that the GaAs buffer layer (BL) needed to be annealed at 600ºC to give PL intensity comparable with QDs grown on GaAs substrate.

The researchers comment: "The lower PL intensity in the case of QDs grown on a Ge/Si substrate may be attributed to the relaxation of charge carriers to non-radiative recombination centers, such as threading dislocations and APDs, formed at the GaAs/Ge interface and propagating into the GaAs BL and reaching the

QD active region, thereby quenching the QD emission efficiency. We have observed that the post-growth thermal annealing of the GaAs buffer layer prior to the growth of QDs can be a simple and effective tool for improving the luminescence efficiency of the QDs grown on Ge/Si substrates."

The researchers used these techniques to create light-emitting diodes with eight layers of QDs (Figure 3). The n- and p-cladding layers consisted of 1.4μm $Al_{0.4}Ga_{0.6}As$. These layers were grown at more than 600ºC, which can degrade underlying QDs in the case of the p-type cladding. In particular, the high temperature can diffuse gallium into and indium out of the dots, shortening the wavelength of emissions.

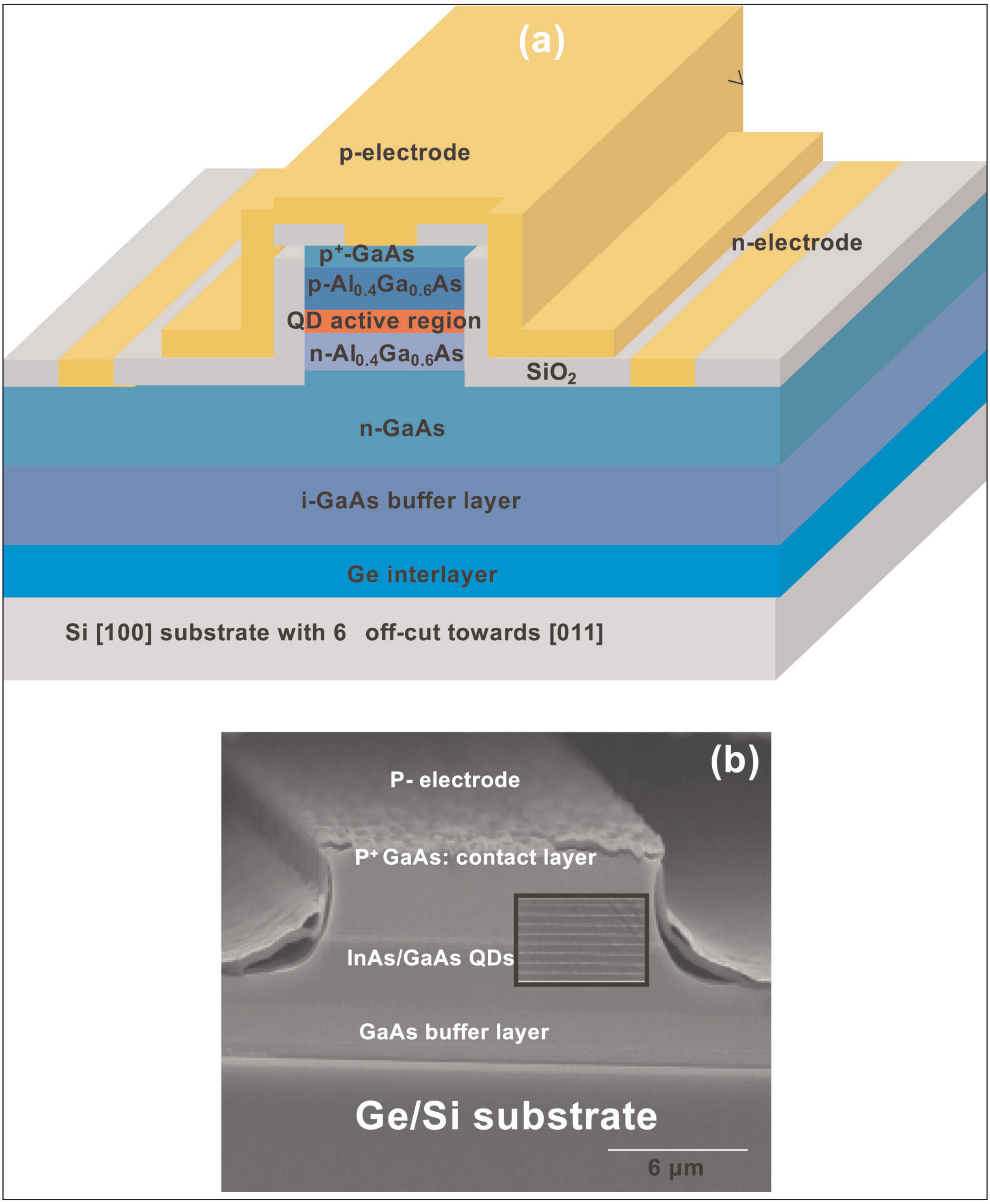

Figure 3. (a) Schematic layer structure of InAs/GaAs QD LED grown on Ge/Si substrate. (b) Cross-sectional high-resolution scanning electron microscope image of fabricated device.

The researchers comment: "The realization of electroluminescence at 1.3μm on Ge/Si, which is not blue-shifted, is attributed to our improved growth conditions of the InAs/Sb:GaAs QDs in the active layer, particularly the Sb irradiation time, before the deposition of InAs, as InAs/Sb:GaAs QDs do not show any blue-shift upon annealing at temperatures as high as 630ºC."

The structure was capped with 300nm p^+-GaAs contact. The contact metal electrodes were gold on gold-germanium-nickel alloy. The electron current injection was lateral from the top side of the device to avoid added series resistance from the high-defect-density GaAs/Ge/Si interfaces.

Under reverse bias the current was of the order 10^{-8}A, suggesting a good rectifying pn junction. Electroluminescence turned on around +0.8V forward bias (Figure 4). Series resistance was around 10Ω. The peak wavelength was 1.3μm with 54meV full-width half-maximum.

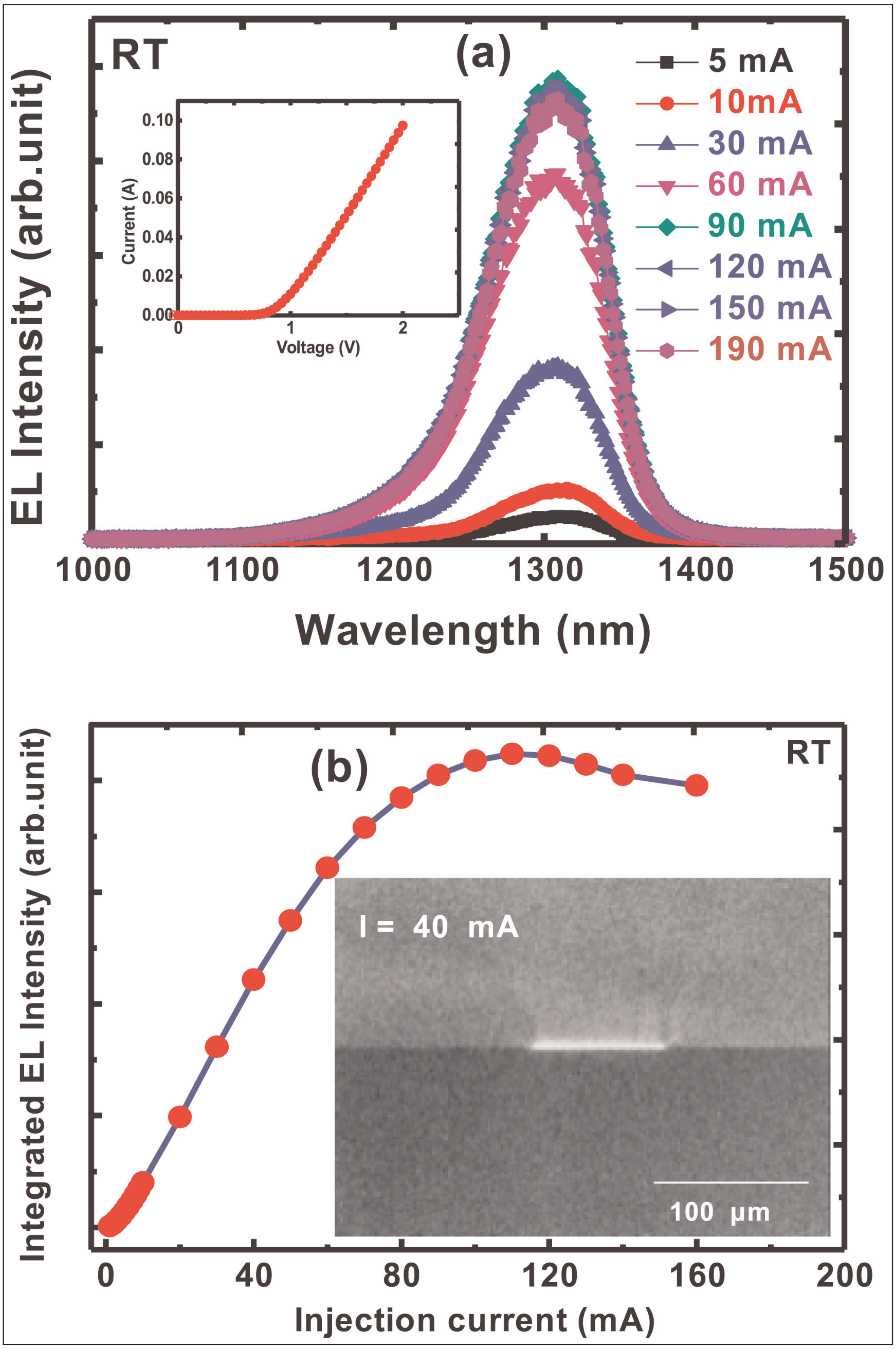

Figure 4. (a) EL spectra of device at room temperature at various injection currents. Inset: current–voltage characteristics of diode. (b) Integrated EL intensity as function of injection current. Inset: infrared camera near-field image of light emission from as-cleaved facet bar at 40mA.

The researchers comment: "To the best of our knowledge, this is the first demonstration of EL at 1.3μm from III–V QDs directly grown on a Ge/Si substrate by MOCVD."

Below 80mA, the increase in intensity with current is approximately linear. With further injection, the output saturates around 130mA and then falls back slightly due to thermal roll-over, non-radiative Auger processes, etc.

The output suffers from imperfect facets because of non-parallel/non-vertical cleavage along the [100] plane. "The combined effect of facet polishing and high-reflection coating on the facets, apart from further improving the uniformity of the QDs in the active region and reducing the defect density in the buffer layer, could potentially lead to the realization of a QD laser on silicon by MOCVD," the team believes.

InGaAs laser diode on exact Ge

Researchers in Russia have developed an InGaAs quantum well laser diode (LD) on (001) Ge-on-Si virtual substrate without offcut angle [V. Ya. Aleshkin et al, Appl. Phys. Lett., vol109, p061111, 2016]. Continuous wave lasing with emission wavelength of 941nm was possible at cryogenic temperatures of 77K. Room-temperature lasing at 992nm wavelength was restricted to pulsed mode.

The researchers hope that in future they will be able to extend the wavelength into the greater than 1.1μm (>1100nm) transparency range needed for use in conjunction with silicon waveguides. "It is assumed that the increase of the In content in the InGaAs QW with an appropriate correction of the QW width could be a possible solution," the team writes.

Normally III–V materials such as InGaAs on (001)-oriented silicon are grown with a significant offcut angle of 4–6º to avoid the formation of antiphase boundaries (APBs), which is a problem for polar materials deposited on non-polar substrates.

However, offcut angles complicate integration with silicon electronics and photonics. In addition, Ge buffers are often used to accommodate lattice mismatching of

Table 1. Parameters of A_3B_5/Ge/Si(001) laser structure.

	Thickness (nm)	Doping (/cm^3)	Remark
Si(001) substrate (upper part)	. . .		Virtual substrate
Ge	~1000	. . .	
AlAs/GaAs/AlAs	10/50/10	. . .	Planarizing buffer
GaAs:Si	2500	2x10^{18}	Main buffer and n-contact
$Al_{0.3}Ga_{0.7}As$:Si	1000	5x10^{17}	Bottom waveguide layer
GaAs	340	. . .	Active region with multiple InGaAs QWs
$In_{0.17}Ga_{0.83}As$ QW	10	. . .	
GaAs	50	. . .	
$In_{0.17}Ga_{0.83}As$ QW	10	. . .	
GaAs	50	. . .	
$In_{0.17}Ga_{0.83}As$ QW	10	. . .	
GaAs	170	. . .	
GaAs:C	170	3x10^{16}	
$Al_{0.3}Ga_{0.7}As$:C	1000	5x10^{17}	Top waveguide layer
GaAs:C	500	2x10^{19}	p-contact

III–V heterostructures with Si, but Ge on offcut Si is generally of low quality. Finally, offcut substrates lead to difficulty when cleaving the final devices into laser bars to give high-quality mirror facets.

The team from Institute for Physics of Microstructures of the Russian Academy of Sciences, Lobachevsky State University of Nizhny Novgorod, and FGUE 'Salut' produced their Ge/Si virtual substrate by solid-source molecular beam epitaxy. The n-Si substrate had a (001) crystal orientation with offcut angle less than 0.5º. A two-step process was used, involving deposition of 50nm Ge at 275ºC and then the remainder at 600ºC. The thin-layer growth allows strain relaxation through misfit dislocations. The higher-temperature growth gives better crystal quality material in the thicker layer. Further improvement was achieved with short-time cycle annealing. The annealing was found to reduce threading dislocation densities from 3–4x10^8/cm^2 to ~10^7/cm^2.

The III–V (A_3B_5) epitaxy involved metal-organic chemical vapor deposition (Table 2). In the initial planarizing buffer, two aluminium arsenide (AlAs) inserts were used to reduce GaAs–Ge interdiffusion and to filter out defects. The AlAs layer also reduced surface roughness by a factor of two.

There were some APBs present due to the use of a substrate with near-zero offcut angle. The APB density in the buffer layer was around 0.6/µm. After the whole structure was grown the density was 0.3/µm. The researchers comment: "These values of the APB density are significantly smaller than the typical ones obtained during growth of polar materials on the exactly oriented non-polar Si(001) substrates. We believe that the influence of the APBs is not the main critical factor affecting the optical properties of the grown A_3B_5/Ge/Si(001) structure."

Laser diodes (Figure 5) were fabricated with the active region 20µm wide, and 200µm-wide planar ohmic contacts of gold-germanium-nickel-gold (n-type) and chromium gold (p-type). The substrate was thinned to 80µm. The material was cleaved into 2.7mm-long bars with mirror facets.

Under electric current injection at 77K (Figure 6), the 941nm-wavelength emission peak narrowed from 30nm below threshold to less than 1nm above. Room-temperature (300K) 992nm emission was 95nm wide

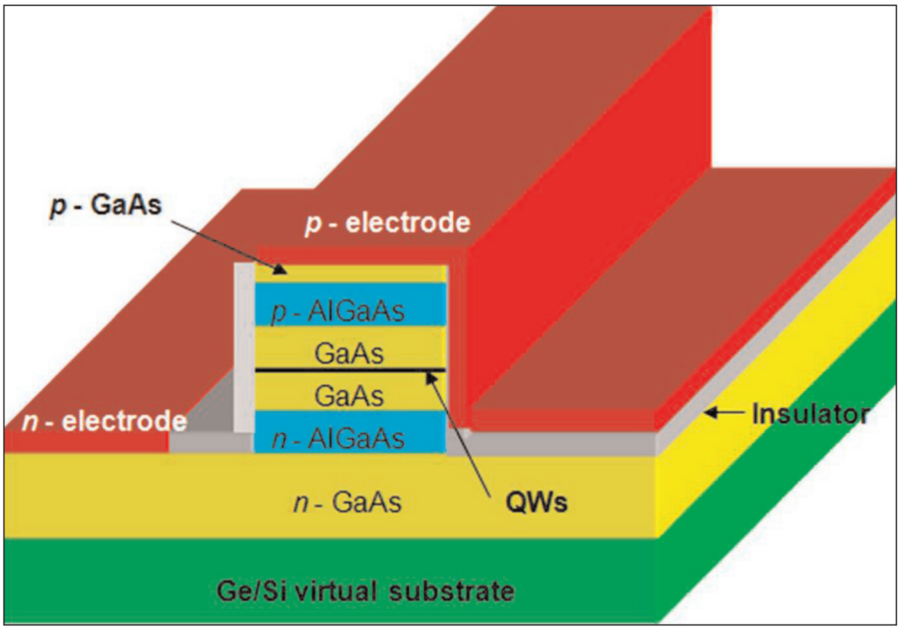

Figure 5. Schematic view of laser diode with planar ohmic contacts.

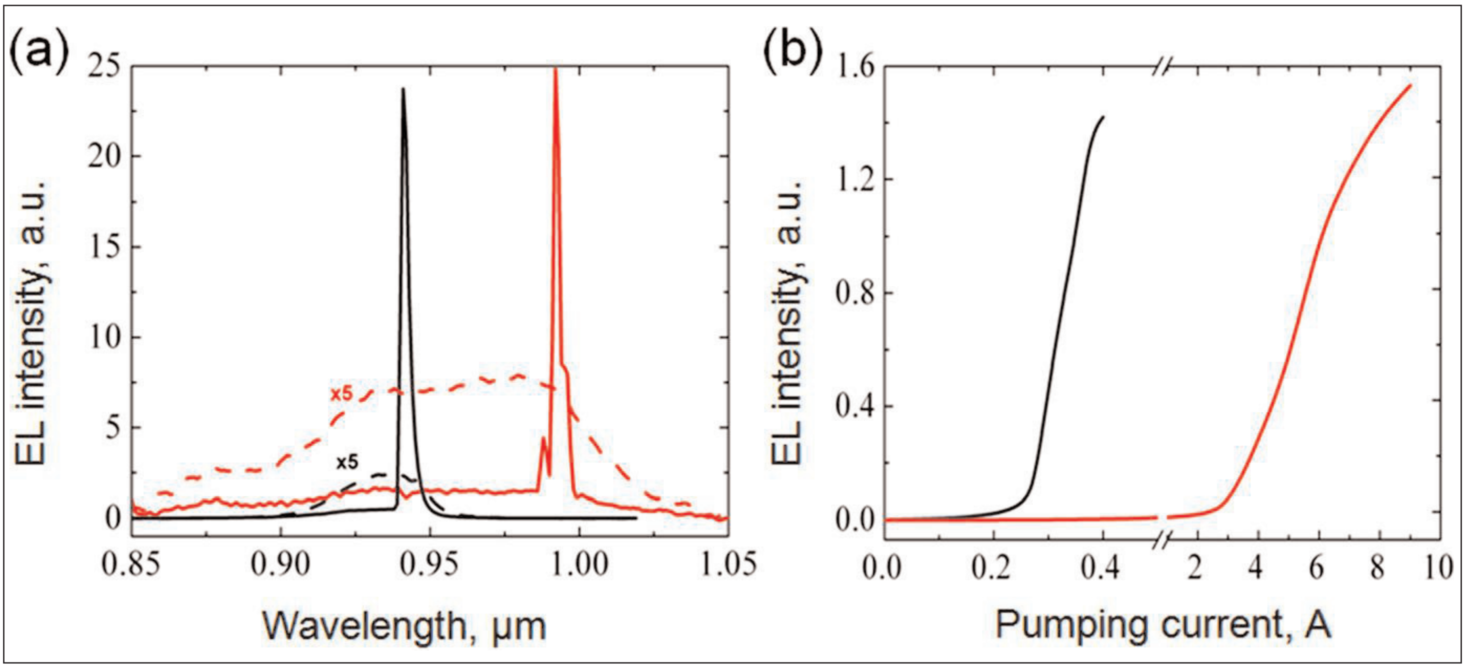

Figure 6. (a) EL spectra at sub-threshold (dashed lines) and above threshold (solid lines). Black lines correspond to 77K, red ones to room temperature. For 77K (300K), pumping current density for subthreshold spectra was approximately 370A/cm^2 (3.7kA/cm^2); and for above threshold spectra 550A/cm^2 (5.6kA/cm^2). (b) Power–current characteristics of the same laser diode.

below threshold and narrowed to less than 1nm above. The threshold for lasing at 77K was 463A/cm^2, low enough for continuous wave operation. At 300K, only pulsed operation was possible with ~5.5kA/cm^2 threshold. ■

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.