Direct growth of InAs quantum dots on silicon

Mike Cooke **reports on recent progress in producing III-V layers on silicon without using wafer bonding, showing potential for wider applications.**

Direct growth of laser and photodiode structures on silicon could lead the way to lower-cost processing, and hence wider commercialization of compact photonic integrated circuits (PICs) on mainstream silicon platforms such as silicon-on-insulator (SOI) waveguides and CMOS electronics. Potential applications include communications, healthcare and energy systems.

Monolithic infrared photodetectors integrated with silicon-based readout electronics could also be used in high-performance, multi-spectral and large-format infrared focal plane arrays for hyperspectral imaging, infrared spectroscopy, and target identification. Other possible uses of such detectors include free-space communication, surveillance, tracking and missile interception, chemical sensing, and biomedical imaging.

Presently, combining laser diode and photodiode technology with silicon often involves tricky wafer bonding techniques. Direct growth of efficient III-V light-emitting semiconductor material on silicon has been hampered by reduced crystal quality due to lattice mismatches between the different crystal layers.

Gallium arsenide (GaAs) growth directly on silicon is hampered by lattice (~4%) and thermal expansion coefficient (TEC) mismatches, which generate dislocations. Better quality direct growth of some III-V materials can be achieved on germanium (Ge) either as a substrate or as an intermediate layer on silicon ('virtual substrate'). However, the presence of germanium can limit the range of accessible silicon electronic circuitry. Also, germanium absorbs the infrared light typically used in optical communications.

Microdisk lasers

Recently, there have been a number of reports on the direct growth of III-V material on silicon that contain indium arsenide (InAs) quantum dot (QD) light-emitting or light-detecting regions, including lasers. Some of the laser devices are not yet at the level of electrical pumping, but do point to future possibilities.

Researchers in Hong Kong and USA have been working on producing optically pumped micro-disk lasers on exact (001) silicon [Yating Wan et al, Appl. Phys. Lett., vol108, p221101, 2016]. The team, from Hong Kong University of Science and Technology (HKUST) and University of California Santa Barbara (UCSB), Sandia National Laboratories and Harvard University in the USA, writes: "We believe that the ultra-low threshold and small-footprint configurations provide significant insights and inspire future possibilities to incorporate efficient and compact laser sources on a CMOS-compatible platform."

The resulting devices had comparable performance to ones produced on GaAs substrates. The use of on-axis substrates is more compatible with mainstream CMOS silicon electronics compared with wafer bonding or epitaxy on offcut substrates with a germanium buffer or direct GaAs nucleation.

Laser emission at around 1.3μm was achieved in 'subwavelength' 1μm-diameter devices. The researchers claim that subwavelength lasing had not been reported in devices produced on silicon before, although it had been on GaAs substrates. In earlier work, almost the same team claimed the first 1.3μm room-temperature continuous-wave (cw) InAs QD microdisk lasers epitaxially grown on industry-compatible Si (001) substrates without offcut [Yating Wan et al, Optics Letters, vol41, p1664, 2016].

A GaAs template layer was produced first, consisting of a 1μm layer of coalesced GaAs on V-grooved silicon (GoVS) grown by metal-organic chemical vapor deposition (MOCVD) — see Figure 1. By growing GaAs first as nanowires in the grooves, followed by coalescence, the resulting template was of high quality and free of anti-phase domains. The lattice mismatch between the GaAs and silicon groove wall was 4.1%. The technique also avoids the use of thick buffer layers and dislocation filters, which are optically absorbing. The transition between the structures was accommodated with a few nanometers of stacking faults (SFs). The SFs were trapped in this region by 'diamond-shaped-pockets' near the top of the grooves.

The researchers see analogies with the aspect ratio trapping (ART) used to integrate III–V high-mobility channel fin field-effect transistors on silicon: "The GoVS templates can thus be envisaged as an extension of III–V fin arrays for optoelectronic devices requiring large active regions, suggesting the possibility of co-integration of silicon photonic and electronic circuits onto the same chip. More importantly, the highly scalable growth technique presented here is

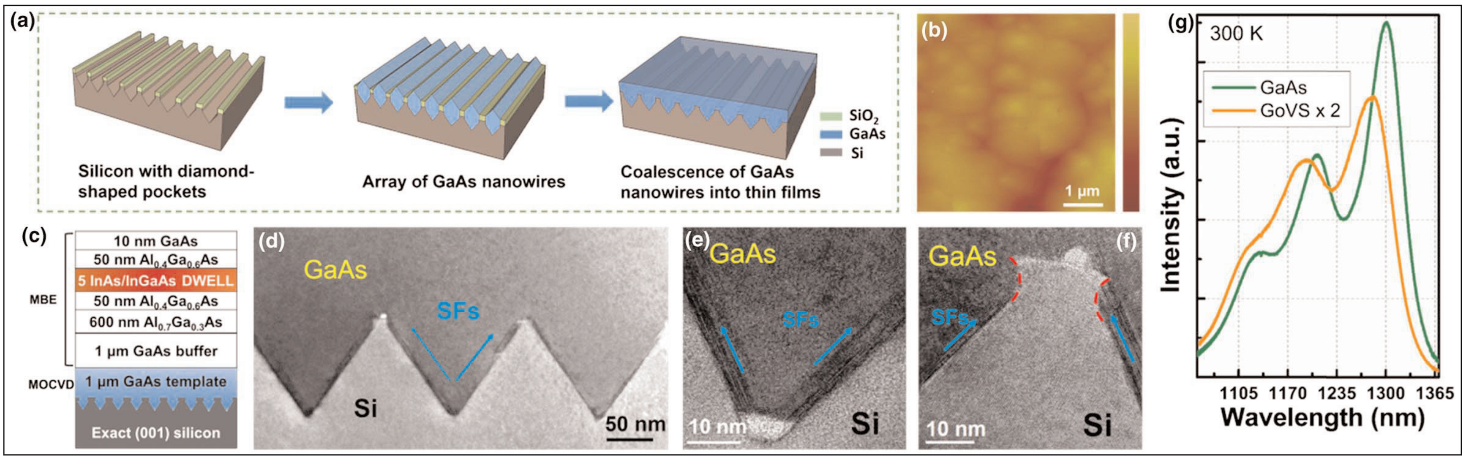

Figure 1. (a) Procedure for growing antiphase-domain-free GaAs thin films. (b) AFM image of coalesced GaAs thin-film grown on nanowire array. Vertical bar is 25nm. (c) Schematic of as-grown structure of microdisk lasers. (d)–(f) Cross-sectional transmission electron micrographs (TEM) of V-groove. (g) Room-temperature photoluminescence spectra of as-grown structures on GoVS template and GaAs substrate.

extendable to the [indium phosphide] InP material system, and can be potentially used for the growth of various heterostructures with ternary and quaternary materials, quantum wells, or QDs on silicon, as evidenced by a recent report of InP distributed feedback [DFB] laser arrays directly grown on silicon."

Since the surface of the GoVS template had low roughness of ~2nm root-mean-square over 5µm x 5µm atomic force microscope (AFM) scans, there was no need for chemical mechanical polishing (CMP). The researchers estimate the GaAs defect density at ~10^8/cm^2, commenting: "Both TEM and x-ray diffraction suggest a three- to four-fold reduction of defects, as compared to blanket heteroepitaxy of GaAs on offcut silicon wafers."

Further layers (Figure 2) were grown by molecular beam epitaxy (MBE) and included a 1µm GaAs buffer and 600nm of Al$_{0.7}$Ga$_{0.3}$As. The active region of the micro-disk laser consisted of five layers of InAs QDs in

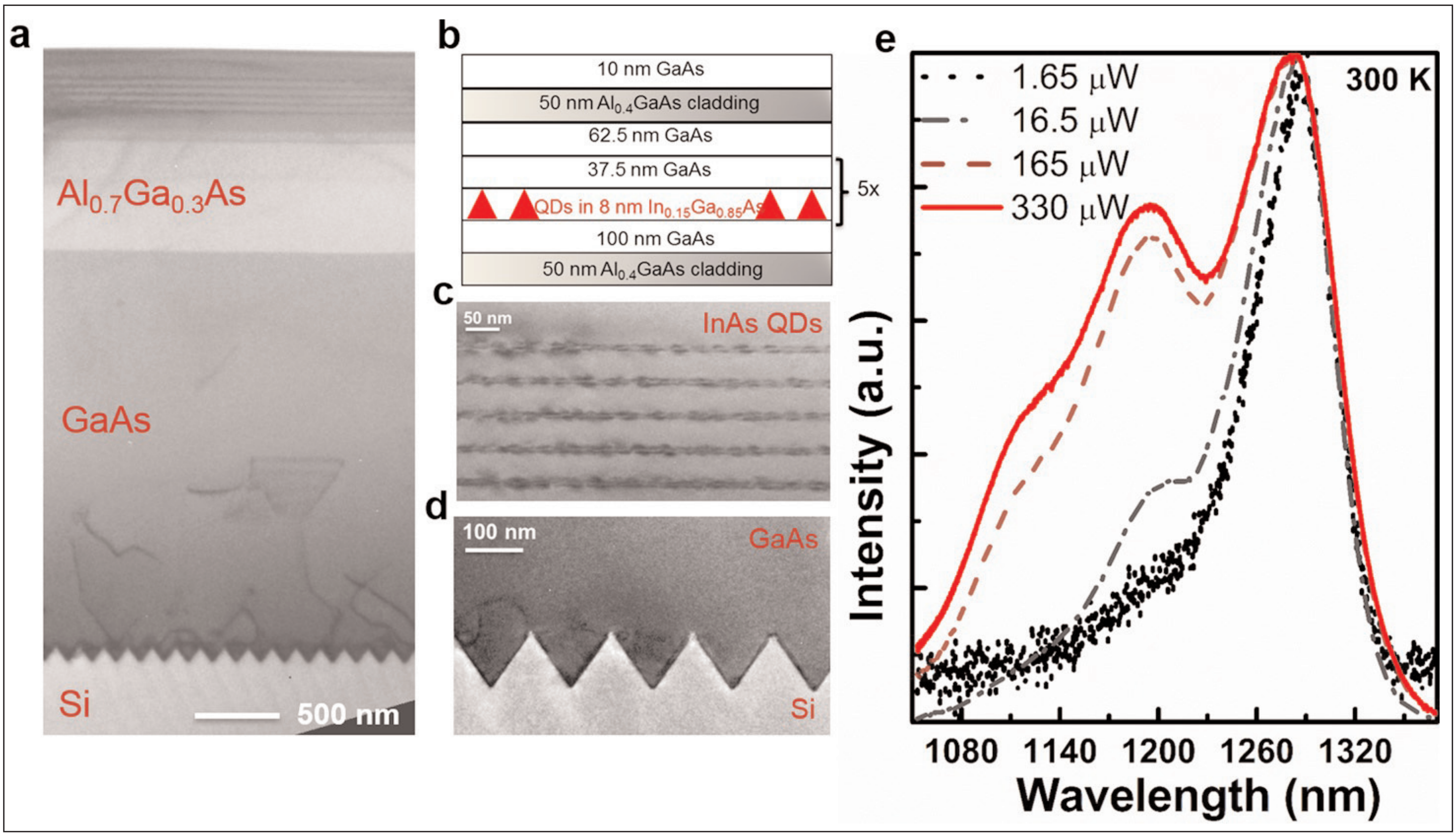

Figure 2. (a) Cross-sectional TEM of micro-disk structure grown on GoVS substrate; (b) schematic epitaxial structure of material in disk region; (c) high-resolution TEM of five-stack InAs QDs; (d) cross-sectional TEM of V-grooved structure, showing defect trapping and localization; (e) room-temperature photoluminescence spectrum of as-grown structure at progressively higher excitations.

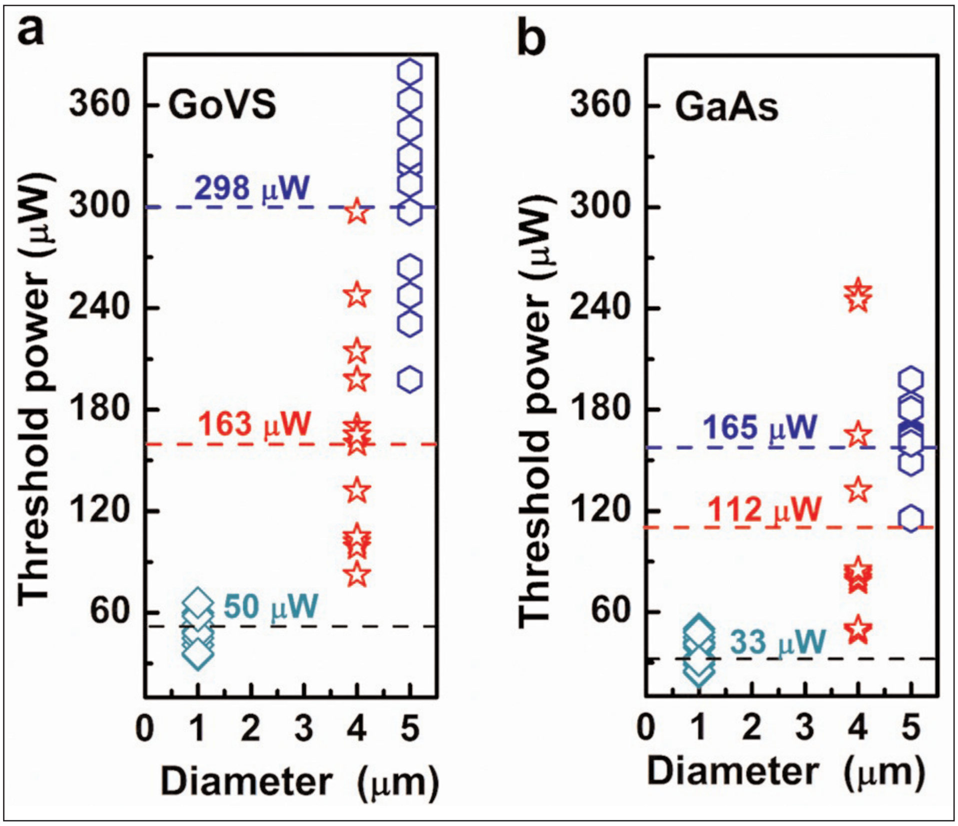

Figure 3. Threshold power as function of disk diameter on GoVS template (a) and GaAs substrate (b). Dashed lines represent average threshold.

InGaAs wells with GaAs barriers. The dot-in-well (DWELL) layers had a dot density of $4.3 \times 10^{10}/cm^2$.

In photoluminescence, the lowest excited-state to ground-state emission was found to be in the 1.3µm optical telecom band. Higher excited states appeared in a high-energy/shorter-wavelength shoulder with increased pumping. "The wide inhomogeneous linewidth (20meV) allows for easy coupling into the resonant modes from small-volume cavities with a large free spectral range (FSR)," the team adds.

The micro-disks were fabricated using lithography based on a colloidal suspension of 1µm-diameter silica beads, which were dispersed on the epitaxial material as a hard mask for inductively coupled plasma etch. The underlying $Al_{0.7}Ga_{0.3}As$ was under-etched with hydrofluoric acid to create pedestals for the micro-disk structures. The pedestal was designed to confine the optical modes to the disk and avoid evanescent coupling of electromagnetic energy into the underlying substrate.

Continuous-wave pumping with light from a 532nm diode laser at 10K showed evidence of lasing in the form of linewidth narrowing. The estimated thresholds came in the range 35–67µW. The average was around 50µW, about 1.5x that for micro-disk layers on GaAs substrate (33µW). "The somewhat larger lasing thresholds on silicon are presumably related to crystalline defects (on the order of $1 \times 10^8/cm^2$ by plan-view transmission electron microscopy) leading to reduced QD modal gain," the researchers comment.

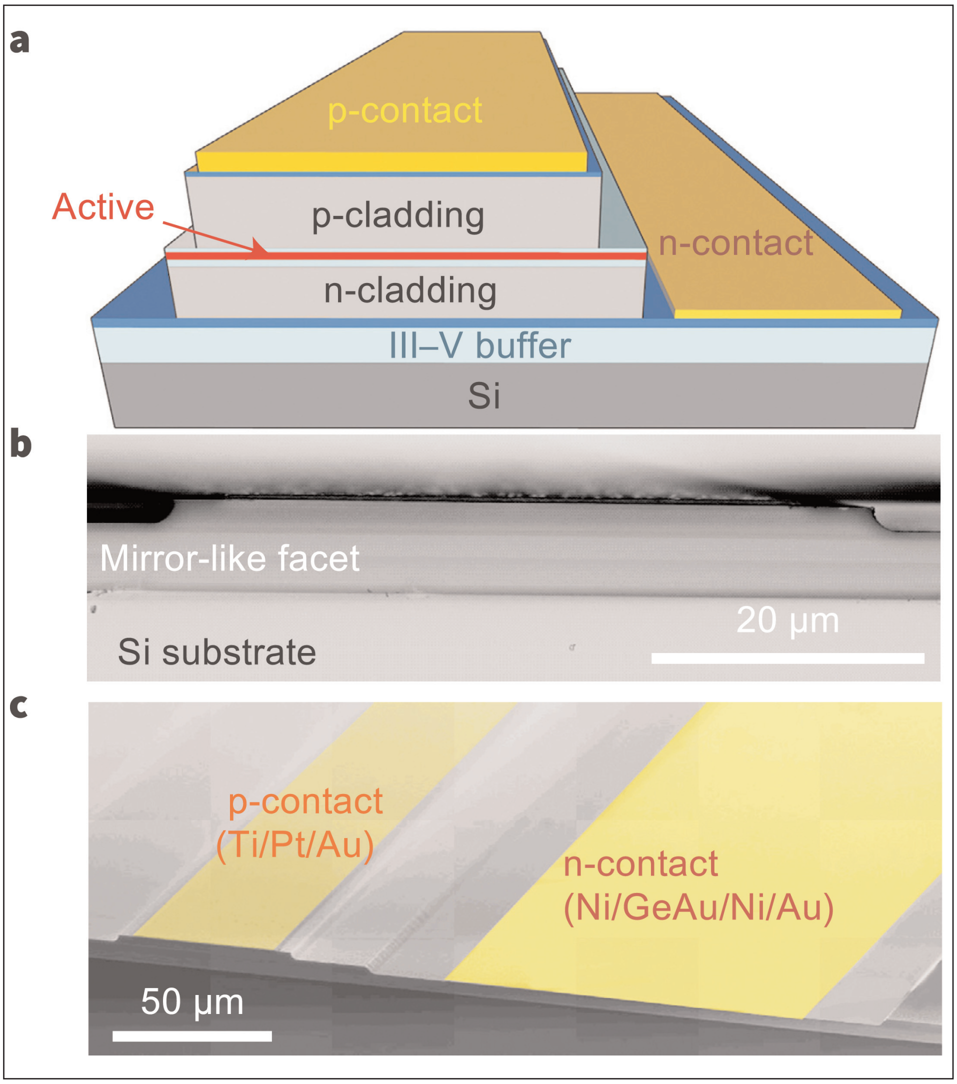

Figure 4. a, Schematic of layer structure of InAs/GaAs QD laser on silicon substrate. b, Cross-sectional SEM image of fabricated laser with as-cleaved facets, showing good facet quality. c, Scanning electron microscope overview of complete III–V laser on silicon.

Larger disk diameters required a higher pump power (Figure 3). The researchers attribute this to the smaller mode separation and thus mode competition. "Due to the mode competition, micro-disk lasers with multi-mode lasing generally show larger thresholds. In addition, the larger disks have larger volumes of material to pump; in particular, the central region of the micro-disk absorbs pump power but has no spatial overlap with the [whispering gallery modes]," the team writes.

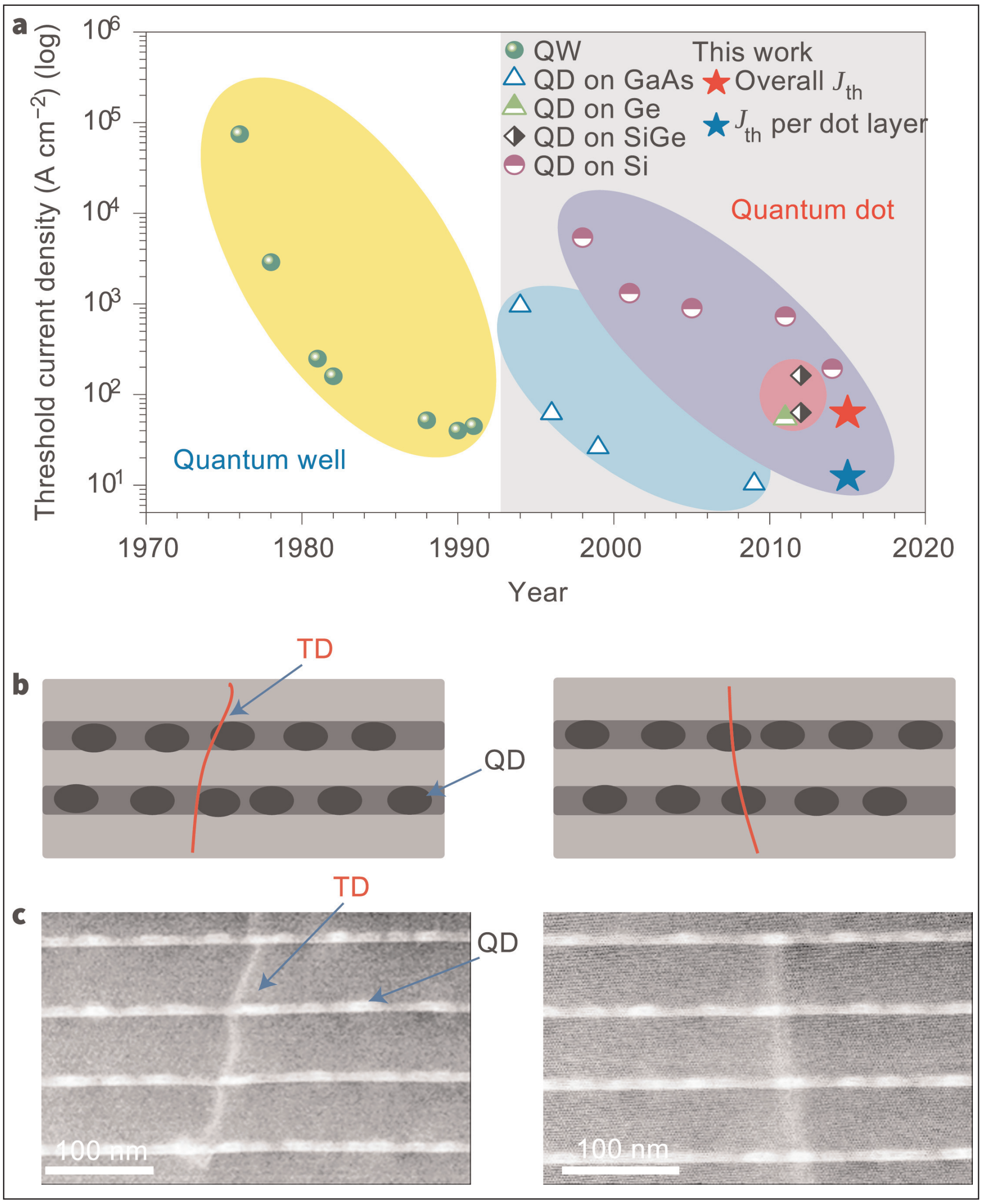

Figure 5. a, Development of low-dimensional heterostructure lasers, showing record threshold current densities. Red (upper) star indicates threshold value achieved. Blue (lower) star is value normalized to single QD layer. b, Schematic of interaction between QDs and threading dislocations. c, Bright-field scanning TEMs showing potential interactions between threading dislocations and QDs.

Laser diodes

Researchers in UK claim the first demonstration of laser diodes grown directly on silicon that perform up to 75ºC and 120ºC under cw and pulsed operation, respectively [Siming Chen et al, Nature Photonics, vol10, p307 2016]. The team from University College London, University of Sheffield, and Cardiff University used a number of techniques to reduce the effect of defects on InAs QDs in GaAs barrier material used for light emission.

The InAs/GaAs materials were grown by MBE on phosphorus-doped n-Si (100). The off-cut angle was 4º to the [011] plane to avoid anti-phase domain formation. A thin 6nm aluminium arsenide (AlAs) nucleation layer was deposited in a 350ºC migration-enhanced process to suppress the three-dimensional growth mode.

Next, a GaAs buffer was grown in three steps: 30nm at 350ºC, 170nm at 450ºC, and 800nm at 590ºC. This confined most defects to the first 200nm of growth, but a significant fraction escaped to give a 1x10^9/cm^2 threading dislocation (T$_D$) density.

To improve material quality, a strained-layer superlattice (SLS) was grown as a dislocation filter. The superlattice consisted of four repeats of five pairs of 10nm/10nm $In_{0.18}Ga_{0.82}As$/GaAs separated by300nm GaAs spacers.

The researchers comment: "The strain relaxation of the SLSs applies an in-plane force to the TDs, which enhances the lateral motion of TDs considerably, and hence increases the probability of annihilation."

In-situ thermal annealing in the MBE reactor was carried out on each of the four SLS sections by raising the temperature to 660ºC for six minutes. This encouraged the TDs to move and annihilate. The SLS dislocation filter was found to reduce TD density to the order of 10^5/cm^2, "beyond the reliable measurement capability of cross-sectional TEM images," according to the researchers.

The ~20nm-diameter ~7nm-high QDs were grown in five dot-in-well (DWELL) layers with a density of about 3x10^{10}/cm^2 and good uniformity. The well layers were 2nm and 6nm $In_{0.15}Ga_{0.85}As$ before and after the dots. The DWELLs were separated by 50nm GaAs spacers. Photoluminescence measurements gave a peak around

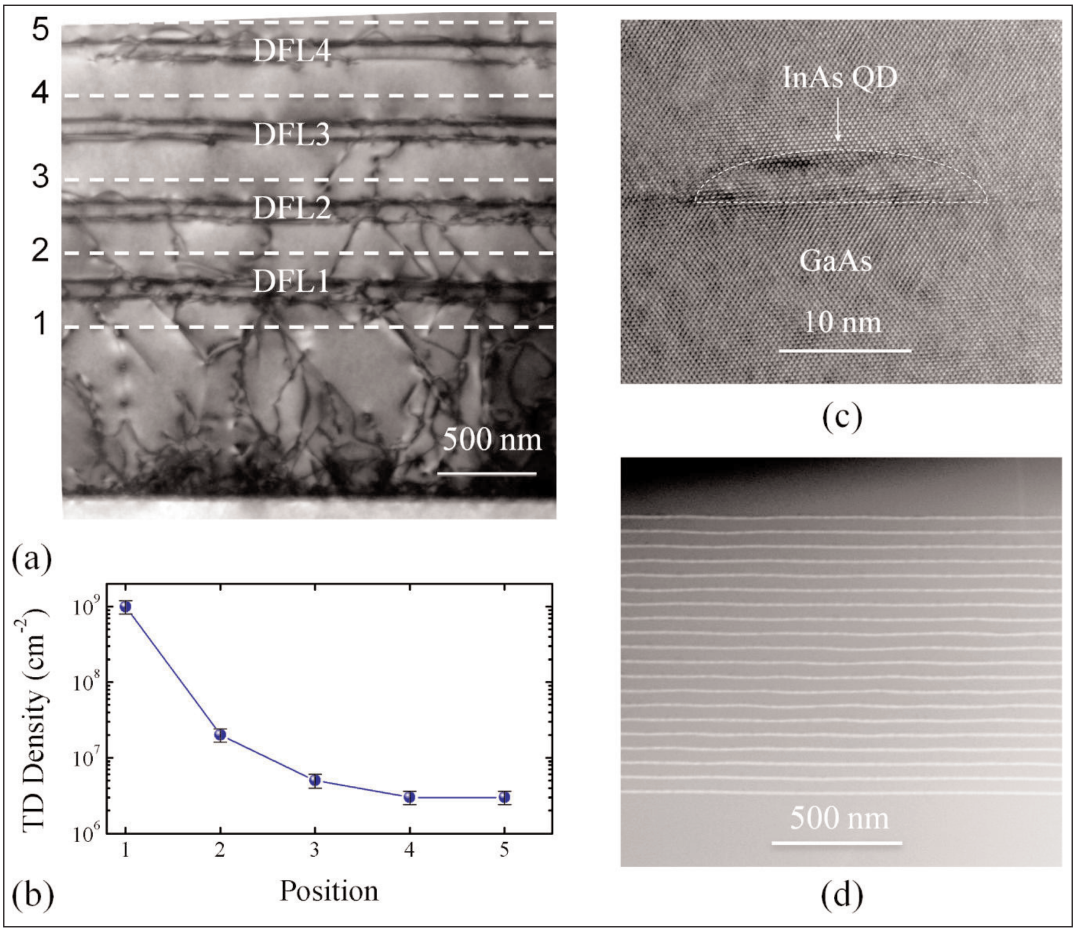

Figure 6. (a) Bright-field multi-beam TEM showing threading dislocation reduction induced by dislocation filter layers. (b) Estimated threading dislocations from TEM measurements at different positions in GaAs buffer as indicated in (a). (c) Representative high-resolution TEM image of single InAs/GaAs QD. (d) Low-magnification bright-field scanning TEM images of 20 layers of QDs.

1300nm wavelength (0.95eV) and 29meV full-width at half maximum (FWHM).

The waveguide was 140nm. Cladding layers were 1.4μm n- and p-type $Al_{0.4}Ga_{0.6}As$. The p-contact was 300nm GaAs.

Broad-area lasers (Figure 4) were fabricated with as-cleaved facets. The laser bars were mounted on gold-plated copper heat-sinks with low-melting-point indium-silver solder. Electrical connections were made with gold-wire bonding.

The threshold current density (J_{th}, Figure 5) was $62.5A/cm^2$ ($12.5A/cm^2$ per QD layer) under cw operation. The researchers comment: "To the best of our knowledge, this value of J_{th} represents the lowest cw room-temperature J_{th} for any kind of laser on a silicon substrate to date and is comparable to the best-reported values for conventional QD lasers on a GaAs substrate."

The output power from both facets reached 105mW with $650A/cm^2$ injection without evidence of saturation.

With a view to the high-temperature operation beyond 65ºC needed for many silicon-based electronic operations, the researchers tested the device under cw and pulsed conditions. The cw lasing was maintained up to 75ºC and pulsed lasing continued up to 120ºC. The 75ºC cw operation was limited by the current source. The researchers claim these as the first high-temperature performance figures for QD lasers grown directly on silicon.

A 3100-hour aging test was also performed at 26ºC and 210mA cw drive current (1.7x threshold). The output power degraded 29.7% over the test period, with the greatest fall in performance (26.4%) occurring in the first 500 hours. The threshold trend was similar. The researchers extrapolate a mean time to failure (MTTF) of 100,158 hours, based on the time needed for a doubling of threshold current.

The team comments: "These data represent the worst-case results, because (1) the laser was operated epitaxial side up, (2) the laser was not hard soldered to a high-thermal-conductivity heat-sink, and (3) no facet coatings were used. Nevertheless, the estimated lifetime is much longer than the best reported extrapolated MTTF of 4627 hours for a p-doped InAs/GaAs QD laser grown on a Ge-on-Si 'virtual' substrate."

Photodiodes

Researchers based in the UK, the USA and Germany have claimed the first direct growth of mid-infrared indium arsenide in gallium arsenide QD infrared photo-detectors (QDIPs) on silicon substrates by MBE [Jiang Wu et al, ACS Photonics, vol3, p749, 2016]. The team came from University College London in the UK, University of Arkansas in the USA, Humboldt University Berlin in Germany, and the United States Army Research Laboratory (ARL).

The team grew III-V material on silicon substrate by solid-source MBE. Anti-phase domains were avoided by growth on (100) substrates offcut 4º in the [011] direction. After a 5nm AlAs nucleation layer, the researchers grew a series of five GaAs buffer layers separated by four InGaAs/GaAs strained-layer superlattice threading dislocation filters (Figure 6). Without a dislocation filter, 1μm GaAs buffers exhibited a dislocation density of 10^9/cm^2. This was reduced to 10^6/cm^3 with the superlattices.

The QDIP structure consisted of a 500nm n-GaAs contact, a 80nm GaAs spacer, a sequence of 20 QD layers separated by 50nm GaAs spacers, a 80nm GaAs spacer, and a 300nm top n-GaAs contact. The InAs dots were formed from a 2.1 monolayer of InAs that coalesced into discs of about 25nm diameter and 5nm height. Photoluminescence (PL) analysis suggested that the dots sizes were quite inhomogeneous.

Studying thermal quenching in the PL above 200K, the researchers estimate an activation energy of 226±27.3eV, which is roughly the difference in energy between the dots' ground state and the GaAs conduction band.

Measurements of the decay of the PL at 10K gave a long lifetime of ~1.3 nanoseconds, comparable to the performance of InAs QDs on GaAs substrate. The researchers comment: "The long decay time signals that the dominant PL decay for the QD states is radiative recombination. Therefore, the long-lived PL in the QDs suggests the GaAs buffer technique used here provides a high-quality QDIP with low defect density."

Mesa QDIPs were fabricated with annealed nickel/germanium-gold/nickel/gold top and bottom contacts. The 1V dark current was "rather low", according to the researchers: 8.9x10^{-4}A/cm^2 at 60K and 2.8x10^{-3}A/cm^2 at 80K (Figure 7). The mesa was 1mm in diameter. The researchers comment: "Despite the presence of threading dislocations (~10^6/cm^2) caused by the large lattice and TEC mismatch, the QDIP on silicon shows comparable dark current density to state-of-the-art devices grown on a native substrate."

The team also points out that its device does not use a current-blocking layer to reduce dark current. The dark current activation energy was 190±1.9meV, which is slightly lower than the photoluminescence thermal quenching value. The hole activation energy is therefore estimated to be ~36meV.

The main peak of the photoresponse was located at 6.5μm wavelength (190.7meV energy), agreeing with the dark current activation energy. The researchers say that this supports a mechanism of bound-to-continuum transitions. The peak was broad with a full-width at half maximum of 2.0μm. ■

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

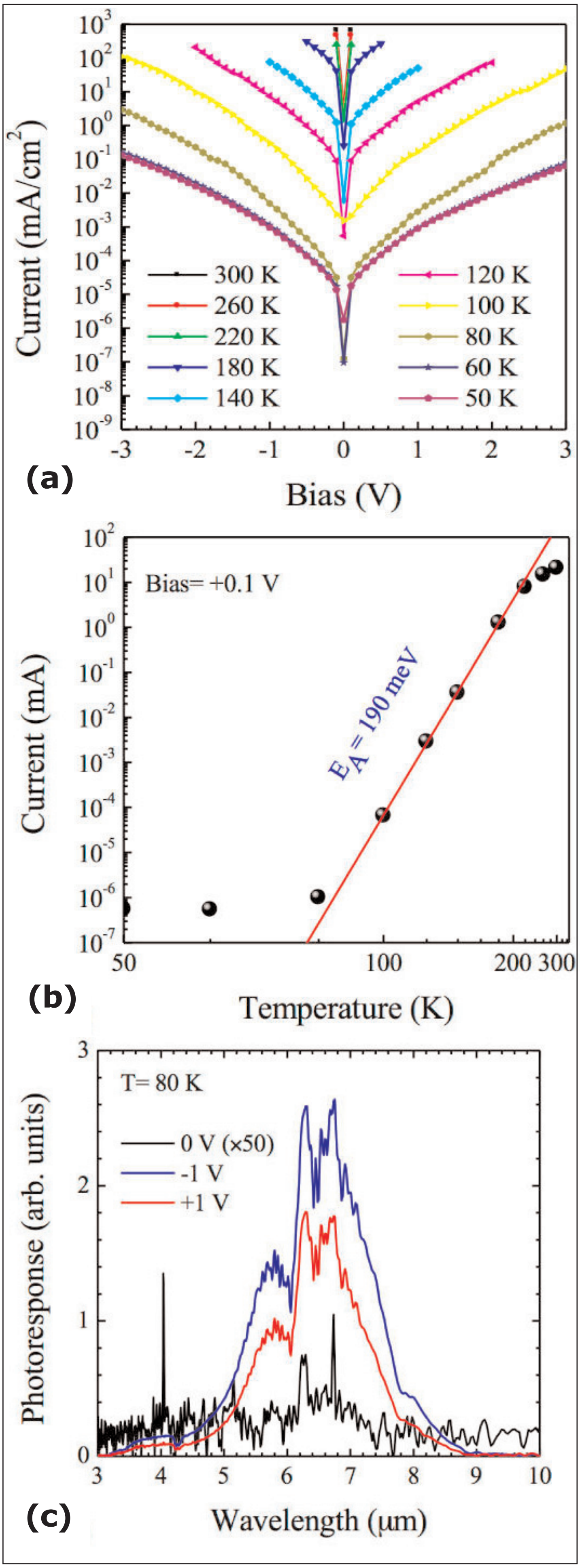

Figure 7. (a) Dark current-voltage characteristics at different temperatures for InAs/GaAs QDIP. (b) Dark current activation energy extracted from dark current measured under 0.1V bias. Fitting error is 1.9meV. (c) Photocurrent spectra measured with different bias voltages at 80K.