LETTERS
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Long-wavelength InAs/GaAs quantum-dot laser diode monolithically grown on Ge substrate

Huiyun Liu[1]*, Ting Wang[1], Qi Jiang[2], Richard Hogg[2], Frank Tutu[1], Francesca Pozzi[1] and Alwyn Seeds[1]

The realization of semiconductor laser diodes on Si substrates would permit the creation of complex optoelectronic circuits, enabling chip-to-chip and system-to-system optical communications. Direct epitaxial growth of III–V semiconductor materials on Si or Ge is one of the most promising candidates for the fabrication of electrically pumped light sources on a Si platform. Here, we describe the first quantum-dot laser to be realized on a Ge substrate. To fabricate the laser, a single-domain GaAs buffer layer was first grown on the Ge substrate using the Ga prelayer technique. A long-wavelength InAs/GaAs quantum-dot structure was then fabricated on the high-quality GaAs buffer layer. Lasing at a wavelength of 1,305 nm with a low threshold current density of 55.2 A cm^{-2} was observed under continuous-wave current drive at room temperature. The results suggest that long-wavelength InAs/GaAs quantum-dot lasers on Si substrates may be realized by epitaxial growth on Ge-on-Si substrates.

Incorporating photonic components into Si microelectronics has been the impetus behind the development of Si photonics for the last twenty years[1,2]. Although Si-based light generation and modulation technologies have been explored extensively[3–5], a Si-based laser has been considered the holy grail of Si photonics because (i) it is the most important active photonic device, (ii) the potential market for Si integrated circuits incorporating electrically pumped lasers is very large, and (iii) it is one of the most difficult challenges to realize among all the Si photonic components[2,6]. Si and Ge have an indirect band structure, which means radiative recombination events do not occur frequently and, accordingly, radiative recombination processes for emitters are insignificant compared to non-radiative recombination[2]. Direct bandgap III–V compounds have robust photonic properties that can be used for many photonics applications. Integrating III–V photonic components with Si microelectronics would thus provide the ideal solution for Si photonics. To date, the most successful approach to the realization of III–V lasers on Si has been hybrid integration using wafer bonding, which has yielded devices capable of operating up to 65 °C (ref. 2). However, despite research activities stretching back over twenty years[7], the direct monolithic integration of III–V lasers on Si substrates continues to present huge implementation challenges.

The most severe problem in III–V on Si integration is the formation of high-density threading dislocations due to the lattice mismatch between III–V compounds and Si (ref. 8). To avoid the formation of threading dislocations, an alternative to direct growth of GaAs on Si is to use an intermediate epitaxial layer, which creates a near-GaAs lattice constant but has few defects. Because the Ge lattice constant is very closely lattice-matched (only 0.08% mismatch) to GaAs, Ge-coated Si layers have been widely used as an ideal 'virtual substrate' for subsequent GaAs growth[9,10]. Note that as the scaling of Si microelectronics devices approaches the 22 nm node, Ge epilayers replace Si as p-channel materials in complementary metal-oxide–semiconductor (CMOS) devices on Si, due to Ge having a much higher hole mobility than Si (ref. 11). Therefore, the major challenge for incorporating III–V photonic components into future Si microelectronics is to fabricate III–V layers directly on Ge-on-Si (Ge/Si) instead of Si (ref. 11).

However, III–V lasers have not become well established on Ge so far because of the formation of antiphase boundaries (APBs), which are planar defects and debilitate device performance. For conventional III–V quantum-well (QW) devices, any threading dislocation or APB propagating through the QWs will become a non-radiative recombination centre, leading to an increased threshold current density J_{th} for III–V QW lasers on Ge and Si substrates[7,12]. In the past decade, III–V quantum dot (QD)—semiconductor nanosized crystal—lasers have been demonstrated with a significantly lower J_{th} than QW lasers and offering temperature-insensitive operation above room temperature[13,14]. Furthermore, QD structures offer other unique advantages over conventional QWs for semiconductor lasers, including lower sensitivity to defects and the special capability of filtering the APBs and threading dislocations[15–18]. In the case of relatively high threading dislocation density in the active region, one threading dislocation in the active region can only 'kill' one or a few dots. It will not affect the majority of dots, so will not significantly degrade the performance of QD devices on Ge or Si substrates[17]. These novel attributes of QD technology are very promising for the development of III–V QD lasers on Ge substrates, and therefore on Ge/Si substrates. Recently, the growth of

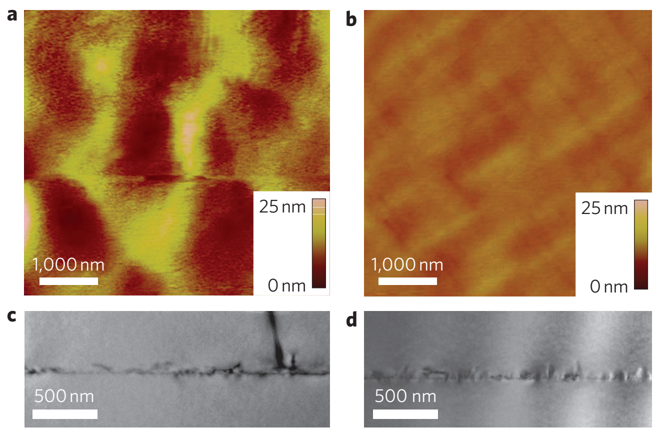

Figure 1 | Structural properties of GaAs buffer layer on Ge substrate. **a**,**b**, AFM images (5 × 5 μm^2) of the surface morphology for 1.2 μm GaAs on Ge substrates with As prelayer (**a**) and Ga prelayer (**b**) growth techniques. **c**,**d**, TEM images of the interface between the GaAs buffer layer and the Ge substrate with As prelayer (**c**) and Ga prelayer (**d**) growth techniques.

[1]Department of Electronic and Electrical Engineering, University College London, London WC1E 7JE, UK, [2]Centre for Nanoscience and Technology, University of Sheffield, North Campus, Broad Lane, Sheffield S3 7HQ, UK. *e-mail: h.liu@ee.ucl.ac.uk

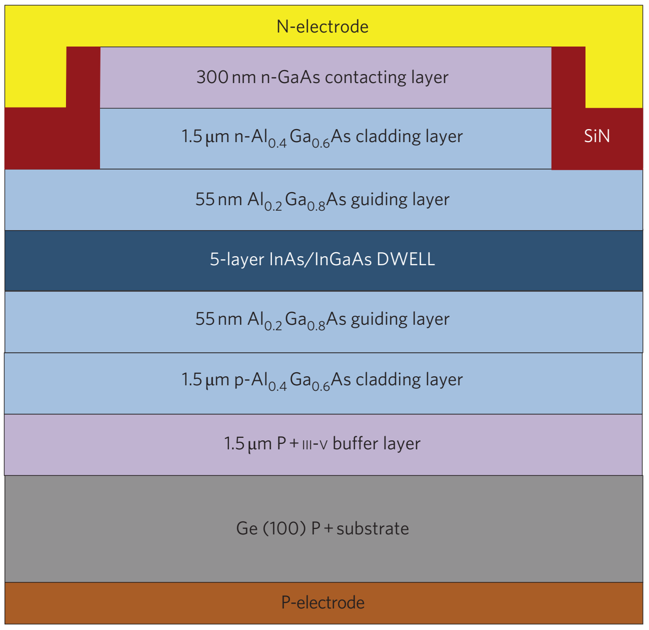

Figure 2 | InAs QD laser diode on a Ge substrate. Schematic showing the layer structure of an InAs/InGaAs DWELL laser diode on a Ge substrate.

InAs/GaAs QDs on a Ge substrate has been demonstrated[19,20]. However, the emission wavelength of InAs/GaAs QDs on Ge is only ~1.1 μm below room temperature[19,20], and there has been no report yet of the realization of lasers.

Here, we describe the first III–V QD laser on a Ge substrate. We first investigated the molecular beam epitaxy (MBE) growth of GaAs buffer layers on (100) Ge substrates, off-cut 6° towards the [111] plane with the As or Ga initial layer. Initiation of GaAs with the typical procedure of using a self-terminating As layer produces poor GaAs surface morphology due to APBs (Fig. 1a), despite the large miscut of the (100) surface. A very much smoother surface morphology for the GaAs layer (Fig. 1b) was obtained by using the Ga prelayer technique, and indicates the formation of a single-domain GaAs buffer layer on the Ge substrate[16]. Transmission electron microscopy (TEM) studies indicate that the defects are only observed within 150 nm of the GaAs/Ge interface for the sample using the Ga prelayer approach (Fig. 1d). The formation of defects at the GaAs/Ge interface is due to the relaxation of strain between the GaAs and Ge in the case of a thick GaAs layer. For the sample with an As prelayer, APBs are generated at the GaAs/Ge interface and propagate into the GaAs buffer layer (Fig. 1c).

A five-layer InAs/InGaAs dot-in-a-well (DWELL) laser structure was fabricated on the single-domain GaAs buffer layer. The device structure of the QD laser on a Ge substrate is shown in Fig. 2. Figure 3a shows a series of room-temperature spontaneous and lasing spectra for a QD laser on a Ge substrate operating below and above threshold. The laser was driven in continuous-wave (c.w.) mode. Spontaneous emission can be observed at a peak wavelength of ~1,306 nm with FWHM = 35 meV at a current of 100 mA. Lasing emission with a peak wavelength of 1,305 nm can be observed at a current of 200 mA (Fig. 3a). On increasing the injection current, the multimode lasing spectrum appears. Similar behaviours in the electroluminescence emission with increasing current were obtained for the reference GaAs-based QD lasers, with room-temperature lasing at 1,301 nm.

The light output power/current (L–I) characteristics under c.w. operation at room temperature are compared in Fig. 3b for InAs/GaAs QD lasers grown on GaAs and Ge substrates, respectively. The lasing threshold is 138 mA for the Ge-based devices, and 134 mA for the GaAs-based arrangement. This slightly higher threshold current for the QD laser on a Ge substrate could be due to current leakage associated with defects at the GaAs/Ge interface. J_{th} for the QD laser on Ge is 55.2 A cm^{-2}, which corresponds to ~11 A cm^{-2} for each of the five QD layers. This very low J_{th} is comparable to the best-reported values for GaAs-based QD lasers, such as 32.5 A cm^{-2} for three-QD-layer lasers[21] and 10.5 A cm^{-2} for single-layer devices[22]. The measured output power from one facet is close to 28 mW for the QD laser on Ge, compared with 54 mW for the device on GaAs, at an injection current of 500 mA (Fig. 3b). This indicates that the differential external quantum efficiency η_{ex} for the laser grown on GaAs is ~1.9 times greater than that on Ge. The difference in η_{ex} between these two substrates could be associated with laser facet quality. The 6° offcut Ge substrates do not cleave smoothly along {110} planes, leading to imperfect cleaved mirrors for the QD devices grown on Ge. Note that mirror reflectivity is strongly dependent on cleave angle. The reduced mirror reflectivity from imperfect cleaved facets of Ge-based QD devices could dramatically reduce the output power. The voltage/current (V–I) characteristics of the QD devices are also shown in Fig. 3b, from which it can be seen that the operating voltage at threshold is 1.7 V with a series resistance of ~2.85 Ω for

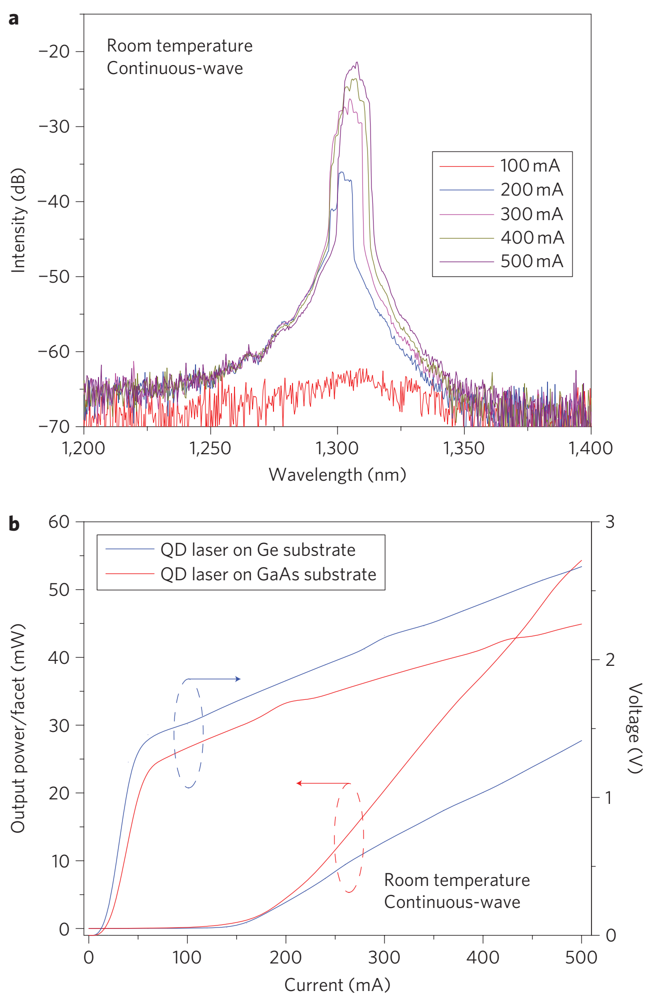

Figure 3 | Room-temperature emission spectra, light output power and electrical characteristics. a, Emission spectra of the five-layer Ge-based InAs/GaAs QD laser for different drive currents below and above threshold. **b**, Light output power versus current and voltage versus current for InAs/GaAs QD laser diodes grown on Ge and GaAs substrates.

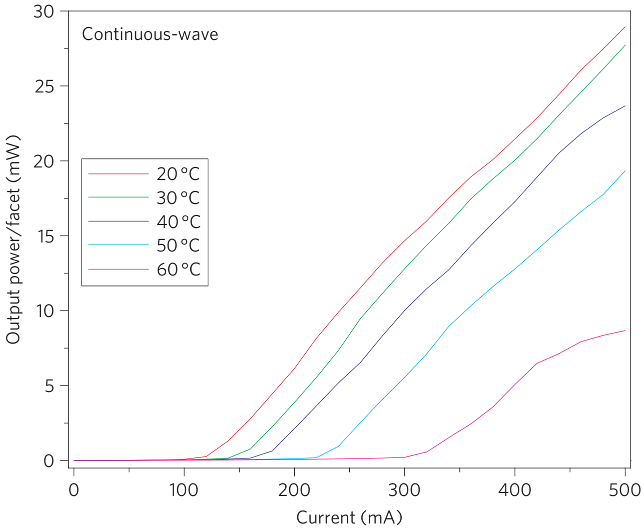

Figure 4 | Temperature-dependent light output power characteristics. Light output versus current for Ge-based InAs/GaAs QD laser at various substrate temperatures.

the Ge-based device, compared with 1.5 V and ~2.25 Ω for the reference GaAs-based device. The defects at the GaAs/Ge interface could contribute to the increased series resistance for the Ge-based device.

Figure 4 shows the c.w. output power per facet for the Ge-based InAs QD laser at various substrate temperatures ranging from 20 °C to 60 °C. The QD laser on Ge has a maximum lasing temperature of 60 °C, with a characteristic temperature T_0 of ~40 K between 20 °C and 60 °C. A similar T_0 value of 40.6 K above room temperature was obtained for the reference GaAs-based device. In general, 1,300 nm InAs/GaAs QD lasers show poor T_0 value in the range of 35–60 K above room temperature, mainly due to the hole excitation out of the lasing state[23,24]. The temperature stability of Ge-based QD lasers could be significantly enhanced by using p-type modulation doping of the QDs, which has been well established to dramatically increase the value of T_0, even to $T_0 \approx \infty$ above room temperature for GaAs-based InAs QD lasers[13,24].

The scheme presented here for growing a QD laser on Ge is very promising for Si optoelectronics. However, lasers on Si substrates are required for such applications. Note that techniques for fabricating low-defect Ge buffer layers on Si have been systematically developed and high-quality Ge/Si wafers are commercially available[25]. A next step towards developing long-wavelength InAs/GaAs QD lasers on Si could be achieved by migrating the laser structure onto Ge/Si substrates. Here, it should be mentioned that although an epitaxially grown Ge/Si laser operating at room temperature has recently been demonstrated, it was pumped optically[26]. Moreover, exactly (001)-oriented Si substrates are required for modern CMOS electronics. By combining atomic layer epitaxy with low-temperature-growth GaAs, high-quality GaAs buffer layers on exactly (001)-oriented Si substrates are achieved with a defect density range from 1×10^4 to 1×10^6 cm^{-2}, which is significantly lower than that (~1×10^8 cm^{-2}) observed in working 1,300 nm InAs/GaAs QD lasers[17,27]. Further improvement of the GaAs buffer layer on exactly (001)-oriented Si substrates could be expected by exploring the growth approach used in this work, so QD lasers on Si may prove realizable.

In conclusion, we have demonstrated the first operation of QD lasers epitaxially grown on Ge substrates. An APB-free GaAs buffer layer has been fabricated by using a Ga prelayer growth technique. Room-temperature c.w. lasing at 1,305 nm has been achieved with an output power of ~28 mW per facet and a very low J_{th} of 55.2 A cm^{-2} for a five-layer QD device. This study is an essential step towards the monolithic integration of long-wavelength InAs/ GaAs QD lasers on a Ge/Si substrate, as well as the integration of other III–V devices by fabricating III–V devices on Ge/Si substrates[11].

Methods

Crystal growth. The epitaxial materials were fabricated by solid-source III–V MBE. Ga-doped (100)-orientated Ge substrates with 6° offcut towards the [111] planes were used in our experiments. The thickness of the Ge wafer was 350 μm. Oxide desorption was performed by holding the Ge substrate at a temperature of 400 °C. The substrate temperature was then increased to 650 °C and held at that temperature for 20 min. The Ge substrate was then cooled to 380 °C for the growth of III–V epitaxial layers. The base pressure was reduced to below 1×10^{-10} torr in the MBE growth chamber before loading the Ge wafer into the growth chamber. For Ga prelayer growth, the main shutter directly covering the Ge was applied after the Ge wafer was loaded in the growth chamber, and opened just before depositing Ga to prevent As deposition on the Ge from the MBE background. To ensure total Ga coverage on the Ge substrate, 1.08-monolayer Ga was first deposited. For As prelayer growth, the Ge surface will be terminated with As by opening the valve of As cracker for 1 min. After deposition of either As or Ga prelayers, 20 monolayers of GaAs were grown by migration-enhanced epitaxy using alternating Ga and As_4 beams, followed by the addition of the III–V buffer layer at higher temperature. QD laser devices containing five InAs/InGaAs DWELL layers were then grown at optimized conditions as on GaAs substrates[14], with each layer consisting of 3.0 monolayers of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and capped by 6 nm of $In_{0.15}Ga_{0.85}As$. GaAs barriers (45 nm) separated the five DWELLs with outer 70 nm GaAs and 55 nm $Al_{0.2}Ga_{0.8}As$ layers completing the waveguide core. Cladding layers consisted of 1.5 μm $Al_{0.4}Ga_{0.6}As$ grown at 620 °C. A 300 nm n^+-GaAs contacting layer completed the growth. The growth temperature was 580 °C for GaAs, and 510 °C for the In-containing layers. To make comparison with a standard GaAs-based InAs QD laser, five-layer 1,300 nm InAs/InGaAs DWELL lasers were fabricated on an n-doped exactly (100)-orientated GaAs substrate with the same growth condition as the QD laser on Ge.

Device fabrication. Broad-area laser devices were formed with a shallow ridge etch after deposition of an Al contact layer on the bottom of the wafer for contacting the Ge substrate. Wet chemical etching was terminated when the upper n-doped GaAs and n-doped AlGaAs layers above the QD active region were removed to a depth of 1.8 μm. A 500-nm-thick layer of SiN_x was deposited on the sample surface and contact windows opened on the ridge top, followed by deposition of the In/Ge/Au contact layer. Similar device processing procedures were used for GaAs-based QD devices with In/Ge/Au for the bottom n-contact layer and Au/Zn/Au for the top p-contact layer. The broad-area devices studied here have a width of 50 μm. Devices with a length of 5 mm were bar-tested, and directly probed without any mounting and bonding.

Measurements. AFM measurements were performed with a Nanoscope Dimension 3100 SPM AFM system in ambient conditions in non-contact mode. Laser device characteristics were measured under c.w. conditions.

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Author contributions

H.L. and A.S. proposed and guided the overall project. H.L., T.W. and F.T. developed and performed material growth and characterization. T.W., Q.J., R.H., F.P. and A.S. were involved with device design, fabrication, measurement and assessment. All authors assisted with preparation of the manuscript and discussed the results.

Additional information

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