1.3 μm InAs/GaAs quantum-dot laser monolithically grown on Si substrates operating over 100°C

S.M. Chen, M.C. Tang, J. Wu, Q. Jiang, V.G. Dorogan, M. Benamara, Y.I. Mazur, G.J. Salamo, A.J. Seeds and H. Liu

A high-performance 1.3 μm InAs/GaAs quantum-dot laser directly grown on Si substrates has been achieved by using InAlAs/GaAs strained-layer superlattice serving as dislocation filter layers (DFLs). The Si-based laser achieves lasing operation up to 111°C with a threshold current density of 200 A/cm^2 and an output power exceeding 100 mW at room temperature.

Introduction: Owing to the limitations in device speed and performance in Si-based electronics, Si photonics has attracted strong interest in recent years, with steady process being made to achieve ultra-fast optical data processing [1]. Although Si-based light generations and modulation technologies have been demonstrated widely [2–4], progress towards an efficient Si-based laser has been limited because of the indirect bandgap of silicon. In contrast, III–V compound semiconductors have a direct band structure and have had an impressive 'show' in many photonic applications [5, 6]. Monolithic growth of high-performance III–V lasers on Si substrates would therefore provide an ideal test bed for the fabrication of electrically pumped lasers on Si substrates.

However, one of the major roadblocks remaining to be solved has been the formation of high-density threading dislocations (TDs), resulting from the lattice mismatch and thermal expansion coefficient between III–V compounds and Si [4]. It has been clearly demonstrated that any TDs propagating into the active media become a non-radiative recombination centre, and hence debilitate laser performance. Therefore, for direct growth of III–V on Si substrates, dislocation filter layers (DFLs) between Si and III–V active element play a crucial role in reducing the density of TDs [7]. Recently, III–V quantum dots (QDs) have emerged as a promising technique for practical III–V/Si photonics, since it offers several important advantages over traditional III–V/Si quantum well technologies, including the improved tolerance to defects and delta-function-like density of states. As a result, impressive results on QD lasers have been demonstrated on Ge, Ge-on-Si and Si substrates [8–13].

In this Letter, we demonstrate a high-performance InAs/GaAs QD laser directly grown on Si substrates using InAlAs DFLs. The device exhibits lasing at 1.26 μm with a threshold current density of 200 A/cm^2 along with single facet output power exceeding 100 mW at room temperature. Significantly, lasing operation for heat sink temperature up to 111°C has been achieved.

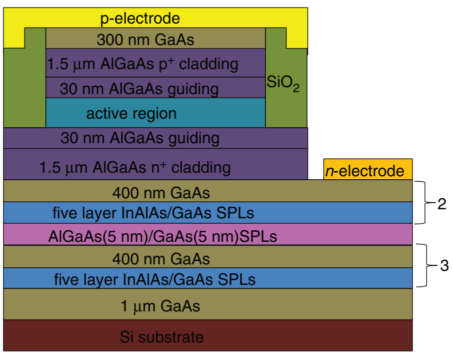

Fig. 1 *Schematic of InAs QD laser directly grown on Si substrates*

Crystal growth and device fabrication: The InAs/GaAs QD laser structure was grown on Si substrates by molecular beam epitaxy. The schematic layer structure is shown in Fig. 1. The epitaxy layer starts with a 1-μm-thick n-type GaAs buffer layer, followed by InAlAs/GaAs DFLs, above this is a 1.5 μm-thick n-type AlGaAs lower cladding layer and a 30 nm-thick undoped AlGaAs guiding layer, followed by the undoped active region. Above the active region, a second 30 nm-thick undoped AlGaAs guiding layer, a 1.5 μm-thick p-type AlGaAs upper cladding layer and finally a 300 nm-thick highly *p*-doped GaAs contact layer was deposited. The active region consists of a five-layer InAs/InGaAs dot-in-a-well (DWELL) structure, consisting of three monolayers of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and capped by 6 nm of $In_{0.15}Ga_{0.85}As$. The InAs/InGaAs DWELLs were separated by 45 nm GaAs spacer layer. For the growth of InAlAs/GaAs DFLs, first three repeats of five periods of a 10 nm $In_{0.15}Al_{0.85}As$/10 nm GaAs superlattice were grown, with each layer of DFLs being separated by a 400 nm GaAs barrier, followed by 50 periods of GaAs (5 nm)/AlGaAs (5 nm) superlattice, above this is grown another two repeats of five periods of a 10 nm $In_{0.15}Al_{0.85}As$/10 nm GaAs superlattice.

Broad-area lasers were fabricated following standard lithography and wet etching techniques. The device described in this Letter was processed with as-cleaved facets and was 25 μm in width and 3 mm in length. No facet coating is applied. Unless otherwise stated, device characterisation was performed under pulsed operation with 1% duty cycle and 1 μs pulse-width to minimise the self-heating of the device.

Structure properties of InAs QD grown on Si substrates: To investigate the effect of InAlAs/GaAs strained-layer superlattices (SLSs) serving as DFLs, transmission electron microscopy (TEM) was performed as shown in Fig. 2*a*. The reduction of dislocation density governed by InAlAs/GaAs SLSs, determined by etch-pit defects (EPDs) and TEM observation, is shown in Fig. 2*b*. As seen, owing to the larger lattice mismatch, an extremely high density (~5×10^9 cm^{-2}) of dislocations is generated at the GaAs/Si interface. Thanks to the InAlAs/GaAs SLSs DFLs, after the last set of InAlAs/GaAs SLSs, the dislocation density has been remarkably reduced to ~3–5×10^6 cm^{-2}. It is clear to see from Fig. 2*c* that no dislocation has been observed in the active region. These observations suggest that the InAlAs/GaAs SLSs can effectively suppress the propagation of TDs into the active region by bending TDs into the growth plane. Atomic force microscopy (AFM) and photoluminescence (PL) measurements were also carried out on uncapped InAs QDs as shown in Figs. 2*d* and *e*, respectively. The dot density is estimated to be ~4×10^{10} cm^{-2}. Strong PL emission at about 1.28 μm with a narrow linewidth of 30 meV is also observed.

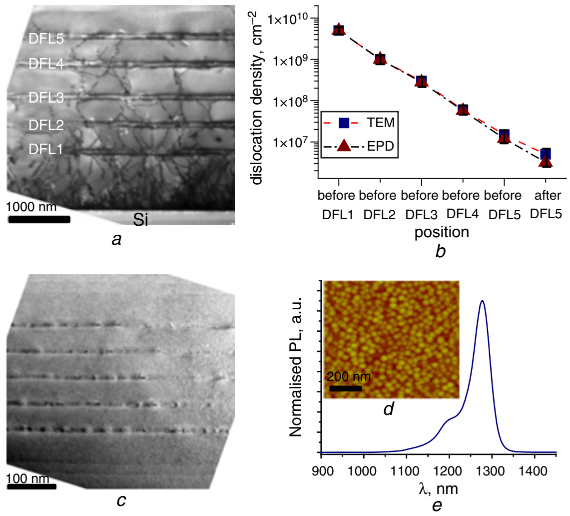

Fig. 2 *Characterisation of material properties of InAs QD directly grown on Si substrates*

a Cross-sectional TEM image of DFLs
b Changes in dislocation density, determined by TEM and EPD
c Cross-sectional TEM image of active region
d AFM image of InAs QDs grown on Si substrates
e Normalised PL spectrum of InAs QD material grown on Si substrates

Results and discussion: Fig. 3*a* shows the output power against the current density at room temperature. A threshold current density of 200 A/cm^2 is achieved, which is much lower than the previously reported values [9, 14]. The measured single facet output power is 101 mW at an injection current density of 1.2 kA/cm^2, with no evidence of power saturation up to this current density. Fig. 3*b* shows the light emission spectra for the current densities below and just above the threshold, in which room temperature lasing at ~1.25 μm is observed. Fig. 4*a* shows the output power for Si-based InAs QD laser at various temperatures. A maximum lasing temperature of 111°C is achieved, which has been further confirmed by the lasing spectrum as presented in Fig. 4*b*, in which a lasing peak at ~1.29 µm is clearly observed. To the best of our knowledge, this is the highest lasing temperature for InAs/GaAs QDs lasers directly grown on Si substrates.

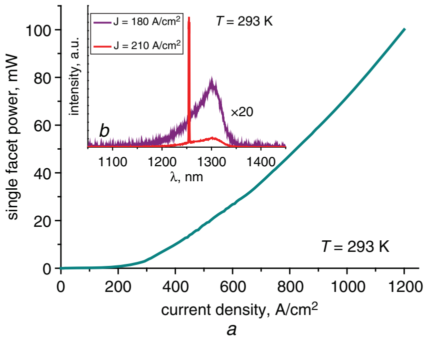

Fig. 3 *Device characterisation at room temperature*

a Light output against current density for InAs QD laser on Si substrate
b Emission spectra for current densities below and just above threshold

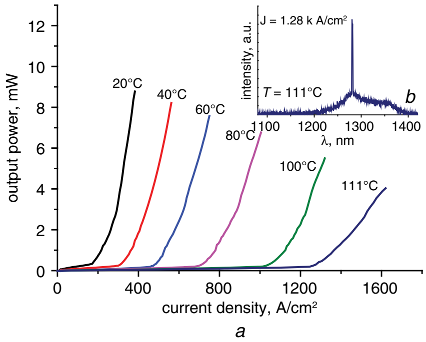

Fig. 4 *Device characterisation as function of temperature*

a Light output against current density for InAs QD laser on Si substrate at various temperatures
b Lasing spectrum just above threshold at 111°C

Conclusion: We have demonstrated high-performance InAs/GaAs QD lasers directly grown on Si substrates using InAlAs/GaAs DFLs. A low-threshold current density of 200 A/cm^2, high single facet output power over 100 mW and lasing operation up to 111°C have been achieved from an as-cleaved broad-area laser of width 25 µm and length 3 mm.

Acknowledgment: The authors acknowledge the financial support from the UK EPSRC under grant no. EP/J012904/1.

This is an open access article published by the IET under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0/)
8 July 2014
doi: 10.1049/el.2014.2414
One or more of the Figures in this Letter are available in colour online.

S.M. Chen, M.C. Tang, J. Wu, Q. Jiang, A.J. Seeds and H. Liu (*Department of Electronic and Electrical Engineering, University College London, London WC1E 7JE, UK*)

E-mail: siming.chen@ucl.ac.uk

V.G. Dorogan, M. Benamara, Y.I. Mazur and G.J. Salamo (*Institute for Nanoscience and Engineering, University of Arkansas, Fayetteville, AR 72701, USA*)

References

1 Liang, D., and Bowers, J.E.: 'Recent progress in lasers on silicon', *Nat. Photonics*, 2010, **4**, pp. 511–517
2 Reed, G.T., Mashanovich, G., Gardes, F.Y., and Thomson, D.J.: 'Silicon optical modulators', *Nat. Photonics*, 2010, **4**, pp. 518–526
3 Michel, J., Liu, J., and Kimerling, L.C.: 'High-performance Ge-on-Si photodetector', *Nat. Photonics*, 2010, **4**, pp. 527–534
4 Chen, R., Tran, T.-T., Ng, K.W., Ko, W.S., Chang, L.C., Sedgwick, F. G., and Chang-Hasnain, C.: 'Nanolasers grown on silicon', *Nat. Photonics*, 2011, **5**, pp. 170–175
5 Liu, H., Childs, D.T., Badcock, T.J., Groom, K.M., Sellers, I.R., Hopkinson, M., Hogg, R.A., Robbins, D.J., Mowbray, D.J., and Skolnick, M.S.: 'High-performance three-layer 1.3 µm InAs-GaAs quantum-dot lasers with very low continuous-wave room-temperature threshold currents', *IEEE Photonics Technol. Lett.*, 2005, **17**, pp. 1139–1141
6 Chen, S., Zhou, K., Zhang, Z., Orchard, J., Childs, D.T., Hugues, M., Wada, O., and Hogg, R.A.: 'Hybrid quantum well/quantum dot structure for broad spectral bandwidth emitters', *IEEE J. Sel. Top. Quantum Electron.*, 2013, **19**, (4), p. 1900209
7 Yamaguchi, M., Sugo, M., and Itoh, Y.: 'Misfit stress dependence of dislocation density reduction in GaAs films on Si substrates grown by strained layer superlattices', *Appl. Phys. Lett.*, 1989, **54**, (25), pp. 2568–2570
8 Liu, H., Wang, T., Jiang, Q., Hogg, R., Tutu, F., Pozzi, F., and Seeds, A.: 'Long-wavelength InAs/GaAs quantum-dot laser diode monolithically grown on Ge substrate', *Nat. Photonics*, 2011, **5**, pp. 416–419
9 Wang, T., Liu, H., Lee, A., Pozzi, A., and Seeds, A.: '1.3 µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates', *Opt. Express*, 2011, **19**, (12), pp. 11381–11386
10 Lee, A., Jiang, Q., Tang, M., Seeds, A., and Liu, H.: 'Continuous-wave InAs/GaAs quantum-dot laser diodes monolithically grown on Si substrate with low threshold current densities', *Opt. Express*, 2012, **20**, pp. 22181–22187
11 Liu, A.Y., Zhang, C., Norman, J., Snyder, A., Lubyshev, D., Fastenau, J.M., Liu, A.W., Gossard, A.C., and Bowers, J.E.: 'High performance continuous wave 1.3 µm quantum dot lasers on silicon', *Appl. Phys. Lett.*, 2014, **104**, pp. 041104–041104-4
12 Tang, M., Chen, S., Wu, J., Jiang, Q., Dorogan, V.G., Benamara, M., Mazur, Y.I., Salamo, G.J., Seeds, A., and Liu, H.: '1.3-µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates using InAlAs/GaAs dislocation filter layers', *Opt. Express*, 2014, **22**, (10), pp. 11528–11535
13 Chen, S., Tang, M., Jiang, Q., Wu, J., Dorogan, V.G., Benamara, M., Mazur, Y.I., Salamo, G.J., Smowton, P., Seeds, A., and Liu, H.: 'InAs/GaAs quantum-dot superluminescent light-emitting diode monolithically grown on a Si substrate', *ACS Photonics.*, 2014, **1**, (7), pp. 638–642, doi:10.1021/ph500162a
14 Mi, Z., Yang, P., Bhattacharya, P., and Huffaker, D.L.: 'Self-organised quantum dots as dislocation filter layers: the case of GaAs-based lasers on silicon', *Electron. Lett.*, 2006, **42**, (2), pp. 121–123