Electrically Pumped Continuous-Wave III-V Quantum Dot Lasers Monolithically Grown On Silicon

Siming Chen1*, Jiang Wu1, Wei Li2, Mengya Liao1, Mingchu Tang1, Qi Jiang1, Samuel Shutts3, Stella Elliott3, Angela Sobiesierski1, Ian Ross2, Peter Snowton3, Alwyn Seeds1 and Huiyun Liu1
1Department of Electronic and Electrical Engineering, University College London, London WC1E 7JE, UK
2Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK
3Department of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, UK
* E-mail address: siming.chen@ucl.ac.uk

Abstract: We demonstrate electrically pumped continuous-wave InAs/GaAs quantum dot lasers monolithically grown on silicon substrates with a low threshold current density of 62.5 Acm⁻², a room temperature output exceeding 105 mW, operation up to 120 °C, and long extrapolated lifetime exceeding 100,000 h.

Keywords: Quantum dot laser, Si photonics, monolithic integration

1. INTRODUCTION
The ability to grow high-quality III-V materials on silicon and then fabricate electrically driven lasers using CMOS-compatible wafer-scale processing methods would enable full-scale development of the silicon photonics platform. However, large material dissimilarity between III-Vs and silicon, especially polar versus nonpolar surfaces and lattice mismatch, makes the monolithic growth of III-Vs directly on silicon substrates highly challenging by introducing high-density antiphase boundaries (APBs) and threading dislocations (TDs) [1]. Recently, III-V quantum dot (QD) based devices have received rapidly growing attention for practical III-V/Si photonics due to their unique properties, in particular reduced sensitivity to defects and delta-function density of states [2-4]. Although much effort has been devoted to optimisation of the III-V epilayers and impressive results have been achieved from QD lasers on silicon substrates [4-7], a high-performance electrically pumped continuous-wave (c.w.) QD laser directly grown on silicon substrate has not previously been demonstrated. Here, we first show that high-quality GaAs epilayers with low density of TDs can be obtained by utilizing the combined strategies of nucleation layer, dislocation filter layers (DFLs) and in situ thermal annealing. We then demonstrate electrically pumped c.w. 1310 nm InAs/GaAs QD lasers directly grown on these epilayers, with an ultra-low threshold current density, high output power, good high temperature performance, and a long extrapolated lifetime.

![Figure 1: Epitaxial growth and structural characterization of QD lasers.](image)

2. EXPERIMENTS
In this work, InAs/GaAs QD lasers were directly grown on silicon substrates using a solid-source molecular beam epitaxy (MBE) system. A detailed description of this laser structure can be found in ref. [8]. To realize high-quality III-V epilayers on silicon and minimize the impact of various types of defects, several strategies have been developed and employed as seen in Figure 1. First, to prevent the formation of APBs while growing polar III-V materials on non-polar silicon substrates, phosphorus-doped Si(100) wafers with 4° offset to the [011] plane were used. To suppress three-dimensional growth and provide a good interface for succeeding III-V material growth, a thin AlAs nucleation layer was deposited by migration enhanced epitaxy at a low growth temperature of 350 °C. To further improve the material
quality, InGaAs/GaAs superlattice structure (SLS) DFLs were grown to effectively suppress the propagation of the TDs. In addition, in situ thermal annealing of SLS was also carried out to further improve the efficacy of filtering defects by increasing the mobility of the defects, leading to their annihilation before growth of subsequent layers. As a result, after the 300 nm GaAs spacer layers of the last SLSs; the dislocation density is reduced to of the order of $10^3$ cm$^{-2}$. Most significantly, a nearly defect-free dot in well (DELL) active region is observed.

![Figure 2: Silicon laser performance characterizations.](image)

Fig. 2(a) shows the output power ($P_{out}$) against current density ($J$) characteristics of a fabricated Si-based InAs QD laser. Device measurements were taken at room temperature under c.w. operation. The measured $P_{out}$ is 105 mW at an injection $J$ of 650 A/cm$^2$. A threshold current density ($J_\text{th}$) of 62.5 A/cm$^2$ is achieved, which corresponds to 12.5 A/cm$^2$ for each of the five QD layers. The inset of Fig. 2(a) (bottom) shows the lasing spectrum just above the threshold, in which room temperature lasing at ~1310 nm is observed. The inset of Fig. 2(a) (upper) shows the $P_{out}$ at various substrate temperatures. C.W. lasing in the ground state was maintained until the testing was stopped at a heatsink temperature of 75 °C, due to the limitation of the c.w. current source. Using pulsed current measurements, lasing at temperatures up to 120 °C was confirmed. Over 3,100 h of c.w. operating data have been collected as presented in Fig. 2(b); the red line is the best-fit curve, governed by a sub-linear model [9], for the measured threshold, from which an estimated lifetime of 100,158 h is extrapolated.

3. RESULTS

Fig. 2(a) shows the output power ($P_{out}$) against current density ($J$) characteristics of a fabricated Si-based InAs QD laser. Device measurements were taken at room temperature under c.w. operation. The measured $P_{out}$ is 105 mW at an injection $J$ of 650 A/cm$^2$. A threshold current density ($J_\text{th}$) of 62.5 A/cm$^2$ is achieved, which corresponds to 12.5 A/cm$^2$ for each of the five QD layers. The inset of Fig. 2(a) (bottom) shows the lasing spectrum just above the threshold, in which room temperature lasing at ~1310 nm is observed. The inset of Fig. 2(a) (upper) shows the $P_{out}$ at various substrate temperatures. C.W. lasing in the ground state was maintained until the testing was stopped at a heatsink temperature of 75 °C, due to the limitation of the c.w. current source. Using pulsed current measurements, lasing at temperatures up to 120 °C was confirmed. Over 3,100 h of c.w. operating data have been collected as presented in Fig. 2(b); the red line is the best-fit curve, governed by a sub-linear model [9], for the measured threshold, from which an estimated lifetime of 100,158 h is extrapolated.

4. CONCLUSION

In summary, we have demonstrated the first practical electrically pumped c.w. 1.310 nm InAs QD lasers directly grown on silicon substrates. We have achieved c.w. lasing up to 75 °C, with an ultralow c.w. $J_\text{th}$ of 62.5 Acm$^{-2}$, a high $P_{out}$ exceeding 105 mW at room temperature and a long extrapolated lifetime exceeding 100,000 h.

REFERENCES