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

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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 ^{o}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.

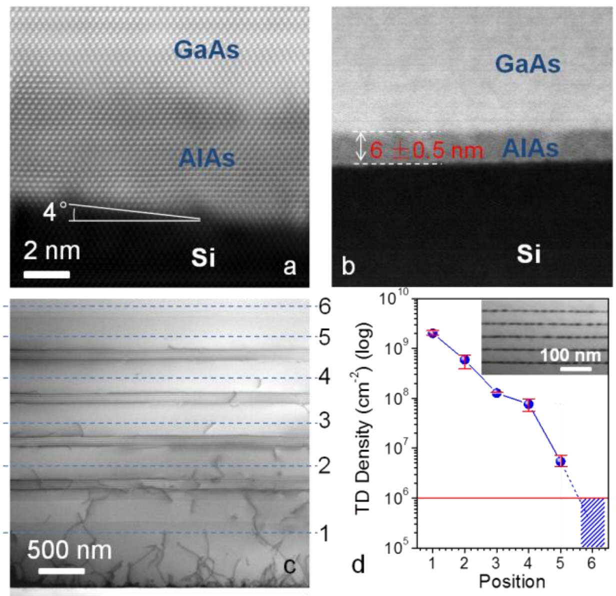

Figure 1: Epitaxial growth and structural characterization of QD lasers. (a) High-resolution high angle annular dark field scanning TEM image of the interface, showing the offcut of silicon substrates is 4°. (b) High-angle annular dark field scanning TEM image of the interface between the 6 nm AlAs nucleation layer and a silicon substrate. (c) Bright-field scanning TEM image of the DFLs. (d) Dislocation density measured at different positions, as labeled in (c). The inset shows the bright-field scanning TEM image of the QD active region.

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° offcut 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 ℃. 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 10^5 cm^{-2}. Most significantly, a nearly defect-free dot in well (DWELL) active region is observed.

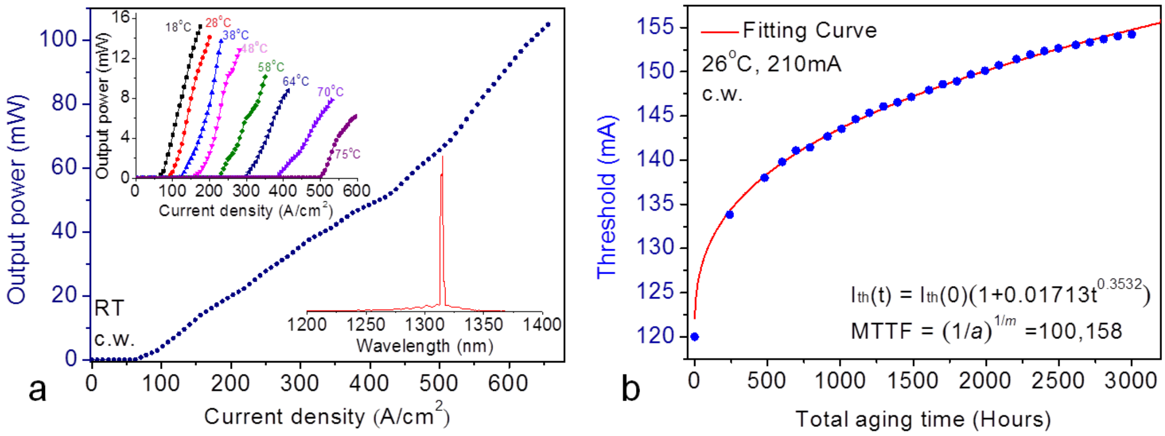

Figure 2: Silicon laser performance characterizations. (a) L-J characteristics for a 50 µm ×3,200 µm InAs/GaAs QD laser grown on a silicon substrate under c.w. operation at room temperature. The inset (bottom) shows the lasing spectrum at 62.5 A/cm^2. The inset (upper) shows the light output power versus current density for this Si-based laser at various heatsink temperatures. (b) Ageing characteristics for the QD laser grown on Si. The blue dots are the measured threshold currents and the red line shows the best-fit curve for the measured threshold current.

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_{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 ^{o}C, due to the limitation of the c.w. current source. Using pulsed current measurements, lasing at temperatures up to 120 ^{o}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 ℃, with an ultralow c.w. J_{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.

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