Room-temperature self-organised In\textsubscript{0.5}Ga\textsubscript{0.5}As quantum dot laser on silicon

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The first room-temperature operation of In\textsubscript{0.5}Ga\textsubscript{0.5}As quantum dot lasers grown directly on Si substrates with a thin (∼2 μm) GaAs buffer layer is reported. The devices are characterised by \( J_\text{th} \approx 1500 \text{ A/cm}^2 \), output power >50 mW and large \( T_\text{0} \) (244 K) and constant output slope efficiency (≥0.3 W/A) in the temperature range 5–95 °C.

Introduction: Future high-speed systems will, in all probability, require the monolithic integration of electronic circuits and optoelectronic components on silicon substrates. An urgent need in such technology is the development of high performance and reliable electronically-injected light sources that can be integrated on silicon in a CMOS-compatible process. Self-organised quantum dot (QD) lasers have recently exhibited superior characteristics compared to their quantum well (QW) counterparts, such as ultra-low threshold current \( (J_\text{th} \leq 100 \text{ A/cm}^2) \) [1], high output power [2], extremely high temperature stability \( (T_\text{0} \geq \infty) \) [3], large small-signal frequency response \( (f_{\text{3 dB}} \approx 25 \text{ GHz}) \) [4], and negligible chirp and linewidth enhancement factors [4]. The first QD laser on Si substrates, reported by Linder et al. [5], was operated at 80 K. It was found that the laser active region had substantially reduced defect densities and the dots themselves may be defect free, which was attributed to the strong strain field surrounding self-organised QDs that inhibits the propagation of dislocations through the dots. This is further confirmed by recent work of Kazi et al. [6], who showed that semiconductor lasers incorporating QD-like structures displayed higher failure resistance and improved reliability compared to similar QW lasers grown on Si substrates. In this Letter, we report the first room-temperature operation of In\textsubscript{0.5}Ga\textsubscript{0.5}As/GaAs QD lasers grown directly on Si substrates. In our samples, the \( \Delta J_\text{th} \) of the QD structure (sample A) grown on Si substrates; and high resolution cross-sectional transmission electron microscopy of one coupled In\textsubscript{0.5}Ga\textsubscript{0.5}As quantum dot layer from laser A.

Experiments: (001)-oriented Si substrates misoriented 4° towards [111] are used to eliminate the formation of antiphase domains and stacking faults at the GaAs/Si interface. A thin (∼2 μm) GaAs buffer layer is first grown by metal organic vapour phase epitaxy. This buffer layer is essentially antiphase domain (APD) free and has surface dislocation densities of \( 2 \sim 5 \times 10^7 \text{ cm}^{-2} \). GaAs/Al\textsubscript{0.4}Ga\textsubscript{0.6}As separate confinement heterostructure (SCH) QD lasers were grown on this thin buffer layer by solid-source molecular beam epitaxy. Two laser heterostructures (hereafter labelled A and B), with slightly different designs in the active region, were grown and characterised. For both samples, the \( p-\) and \( n-\)cladding layers consist of 1.5 μm Al\textsubscript{0.4}Ga\textsubscript{0.6}As layers, doped with Be and Si, respectively. The heterostructure of laser A is shown in Fig. 1a. The active region of laser B consists of five coupled In\textsubscript{0.5}Ga\textsubscript{0.5}As QD layers spaced evenly in a 0.25 μm-thick Al\textsubscript{0.4}Ga\textsubscript{0.6}As waveguide. Each QD layer in laser B is modulation doped \( p-\)type using beryllium, averaging about 20 holes per dot. Acceptor (\( p \)) doping of the QDs has been shown to be an effective technique for reducing the temperature dependence of QD lasers [3, 7]. In addition, an AlGaAs waveguide, instead of GaAs, can provide better carrier confinement in the QDs and reduce carrier leakage. For both lasers A and B, the QD layers were grown at 510°C and the rest of the structure was grown at 620°C. Room-temperature photoluminescence (PL) emission from the quantum dots in both laser heterostructures is comparable in intensity and linewidth (∼60 meV) to that from QD laser heterostructures grown on GaAs substrates. This indicates that high quality quantum dots can be grown, despite the rather large surface dislocation densities. Devices were fabricated by standard photolithography, wet and dry etching and contact metallisation techniques. The Si substrates were thinned down to less than 100 μm to facilitate smooth cleaving along the (110) direction. The heterostructure of laser A was studied by high-resolution cross-sectional transmission electron microscopy (HRXTEM) with a special focus on the device active region. Most of the threading dislocations and antiphase domains are confined near the GaAs/Si interface, as is typically the case for GaAs-based heterostructures on Si substrates. An HRXTEM image of the device active region is shown in Fig. 1b, which indicates that the quantum dots may be almost defect-free. These characteristics are consistent with the strong PL emission measured at room temperature.

Results: The characteristics of laser A are first described. Light-current (I-L) measurements were performed on near-singlemode (400 × 8 μm) lasers under pulsed bias conditions (1% duty cycle) at various temperatures. These devices demonstrate relatively low threshold current \( (J_\text{th} \sim 1500 \text{ A/cm}^2) \) and high output power (>50 mW), as shown in Fig. 2a. The inset in this Figure shows the spectral output at a drive current of 75 mA. Temperature-dependent...
L-I measurements were performed on these devices, and we measured a $T_0$ (given by $I_{th}(T_2)/I_{th}(T_1) = \exp((T_2 - T_1)/T_0)$) of 103 K in the temperature range 5–95°C and a constant output slope efficiency of 0.37 W/A in the same temperature range. The threshold current of 1500 A/cm² is still much higher than comparable QD lasers grown on GaAs substrates, which is typically ~100 A/cm². The threshold current can be further reduced by using low defect density buffer layers such as relaxed and graded GeSi$_x$ buffer layers.

The temperature-dependent L-I characteristics of laser B were measured under pulsed bias for an 800×8 µm² device. The threshold current density at room temperature is about 1700 A/cm², which is slightly higher than sample A and is most likely due to increased Auger recombination upon p-doping [3]. The data are shown in Fig. 2b. The measured $T_0$ is ∞ in the temperature range 5–25°C and 244 K in the temperature range 25–95°C. The higher $T_0$ values in laser B are as expected. The output slope efficiency, also shown in Fig. 2b, remains essentially constant at 0.31 W/A in the temperature range 5–95°C.

Conclusion: We have reported room-temperature operation of InGaAs/GaAs QD lasers grown directly on Si substrates. Despite the use of a thin GaAs buffer layer with relatively high dislocation densities, the preliminary results indicate that QD lasers can be practical light sources on CMOS chips.

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References

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