A room temperature electrically pumped 1.3-µm InAs quantum dot laser monolithically grown on silicon substrates

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Abstract

We present a room-temperature 1.3-µm InAs/GaAs quantum dot laser emitting monolithically grown on Si(100). The threshold current at 20°C was 725A/cm^2 and the emission wavelength was 1.302µm. The laser was operated in pulsed mode. The growth was enabled via the optimisation of the temperature of the initial nucleation layer of GaAs.

Introduction

A laser on silicon is highly desirable for silicon photonics. In addition, this area along with silicon based modulators has been heavily researched [1-5]. However there are two main issues preventing the realisation of an all silicon laser, the indirect bandgap of Si and two photon absorption. An alternative is to monolithically grow conventional III-V compounds on Si [6,7]. There are still many challenges to solve using this technique. Firstly the large lattice mismatch between III-V compounds and Si which can lead to high threading dislocation (TD) densities and secondly the polar/non-polar characteristic of III-V/IV system leads to the formation of antiphase domains (APD) which have a significant effect on the threshold current, J_{th} [8]. In conventional III/V-Si quantum well (QW) lasers any TD or APD in the active layer would lead to the formation of a non-radiative centre, and hence significantly increase J_{th} [9].

The usage of quantum dot (QD) lasers has been shown to lead to lower J_{th} and independent temperature operation when compared to QW lasers [10-12]. In addition to this, QD lasers also have a lower sensitivity to defects than QW lasers. In this work a laser operating at room temperature was grown directly using molecular beam epitaxy (MBE) on Si(100)miscut by 4° towards the [110] plane using a conventional dot in well (DWELL) structure. The laser had an output wavelength of 1.302 µm and a threshold current of 725A/cm^2. The growth was enabled by the temperature optimisation of the initial GaAs nucleation layer and it was found that small changes in temperature could have significant changes in the amount of vertically propagating defects. The initial GaAs layer was grown at 400°C.

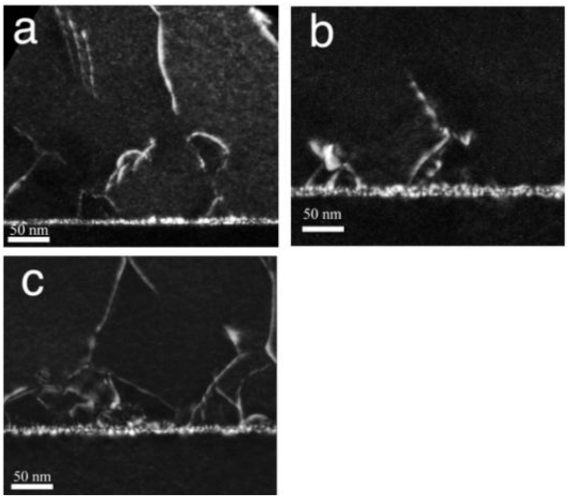

Figure 2 Cross-sectional TEM images of GaAs/Si interface for the initial GaAs nucleation layer grown at (a) 380 °C, (b) 400 °C, and (c) 420 °C.

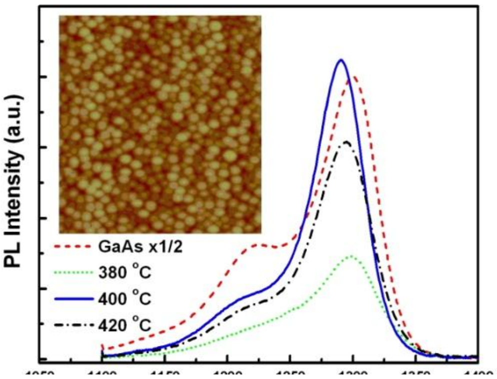

Figure 1 RT PL spectra of InAs/GaAs QDs grown on Si substrates with different growth temperature for initial GaAs nucleation layer. RT PL spectrum of InAs QDs grown on GaAs substrate is also shown as a reference. The inset shows a 1 × 1 µm^2 AFM image of InAs/GaAs QDs grown on Si substrate.

Epitaxial growth and device fabrication

The growth was performed using solid source Molecular Beam Epitaxy. First the Si substrate was heated to 900°C in order to desorb any oxygen on the surface. The sample was then cooled to 400°C. An initial 30 nm layer of GaAs was grown at 400°C at 0.1ML/s. Then the temperature and growth rate were increased to grow a further 970nm of GaAs. It was found that the initial layer of GaAs needed to be optimised with respect to temperature in order to achieve a growth with the lowest density of threading dislocations. This was done by taking the photoluminescence of different samples. The photoluminescence (PL) was performed using the same structure as in figure 2 except the QDs were left uncapped. The effect of the temperature optimisation was further investigated by transmission electron microscopy (TEM). The TEM images in figure 1 clearly show that the threading dislocations propagate far further for 380°C and 420°C than for 400°C. This shows that the defect density has a strong dependence on the low growth temperature of the initial GaAs nucleation layer. After the GaAs nucleation layer, a multi-quantum well (MQW) filter layer was grown. This consisted of two repeats of a five period 10nm layer of $In_{0.15}$ $Ga_{0.85}As$ followed by 10nm GaAs. In addition to this a 1µm superlattice buffer layer consisting of alternating layers of 5nm GaAs and 5nm AlGaAs.

Figure 4 Schematic showing the grown structure

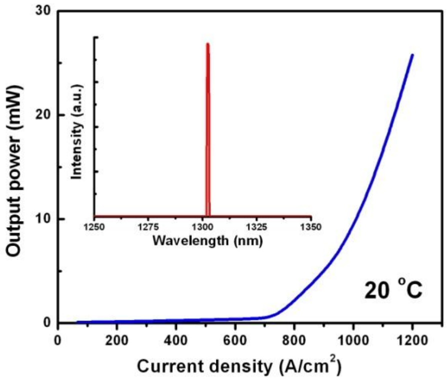

Figure 3 Light output against current characteristic for InAs/GaAs quantum-dot laser on Si substrate under pulsed condition at room temperature. Inset shows the electroluminescence above the threshold.

On top of the superlattice layer a 50nm layer of GaAs was grown and then a standard DWELL structure was grown consisting of 5 layers of 3.0MLs of InAs grown on 2nm of InGaAs. The QDs were then capped with 50nm GaAs. Finally 100nm $Al_{0.4}Ga_{0.6}As$ and 50nm GaAs. The grown structure is shown in figure 3. 50µm broad area stripe lasers with cleaved facets, without high reflectivity (HR) coating, were fabricated with Ti/Au for the top contact and Cr/Au for the bottom contact. Devices of 3-mm length were bar-tested, being directly probed without any mounting and bonding.

Results and Discussion

The room temperature light output against current is shown in figure 4 of the laser fabricated at room temperature. The laser was operated in pulsed mode with a pulse width of 0.1µs and duty cycle of 0.01%. The measured output power is close to 26 mW for an injection current density of 1.2 kA/cm^2, with no evidence of power saturation up to this current. The RT J_{th} is 725 A/cm^2, which is lower than the previously reported value of 900 A/cm^2 for InGaAs/GaAs QD laser directly grown on Si substrate emitting at 1.02µm [4]. Note that this device was processed with as-cleaved facets. The use of high-reflection (HR) coating on the facets in the future studies will further decrease J_{th} [5] The inset of Fig. 4 shows the electroluminescence spectrum above threshold, in which RT lasing at 1.302 µm is observed. The laser was measured from 20°C up to 42°C. The characteristic temperature was found to be 44K, however 1.3µm InAs/GaAs QD lasers on Si typically show poor T_0 in the range of 35-60K[6] and this can be increased by using p-type modulation doping of the quantum dots which has been shown to significantly increase the value of T_0 [10]

Conclusion

The first 1.3-µm emitting QD laser grown directly on Si at room temperature has been demonstrated. The output wavelength was 1.302µm at room temperature with an output power of ~26 mW and J_{th} of 725 A/cm^2 for a five-layer InAs/GaAs QD device on Si substrate. This study is an essential step toward the monolithic integration of long-wavelength InAs/GaAs QD lasers on Si substrate.

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