1.3-µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates

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Abstract: We report the first operation of an electrically pumped 1.3-µm InAs/GaAs quantum-dot laser epitaxially grown on a Si (100) substrate. The laser structure was grown directly on the Si substrate by molecular beam epitaxy. Lasing at 1.302 µm has been demonstrated with threshold current density of 725 A/cm^2 and output power of ~26 mW for broad-area lasers with as-cleaved facets at room temperature. These results are directly attributable to the optimized growth temperature of the initial GaAs nucleation layer.

OCIS codes: (230.5590) Quantum-well, -wire, and –dot devices; (250.5960) Semiconductor lasers; (250.5300) Photonic integration circuits.

References and links

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1. Introduction

Although Si-based light generation and modulation technologies have been extensively investigated, Si-based lasers are still considered to be the holy grail of Si photonics, because they represent one of the greatest challenges to be realised among all the Si photonic components, and they have massive application potential if successful [1–5]. The integration of III-V lasers with Si technology is the most promising near-term approach [1,3]. Among III-V/Si integration approaches, direct epitaxial growth of III-V compounds on Si substrates could be the most desirable [6,7]. But there are severe issues associated with direct epitaxial growth of III-V materials on Si substrates, i.e., the formation of high-density threading dislocations (TDs) due to the lattice mismatch between III-V compounds and Si, and the formation of antiphase boundaries (APBs) due to the polar/non polar nature of the III-V/IV system [8]. For conventional III-V/Si quantum well (QW) devices, any TD or APB propagating through the QWs will become a nonradiative recombination centre, and hence lead to significant increment of threshold current density, J_{th}, for QW lasers [9]. III-V quantum-dot (QD) lasers have recently been demonstrated with a significantly lower J_{th} and more temperature-independent operation than for QW lasers [10–12]. Furthermore, QD lasers have lower sensitivity to defects than QW ones [13]. These novel attributes of QD technology are very promising for the development of III-V/Si lasers by the use of direct epitaxial growth. An InAs/GaAs QD laser directly grown on a Si substrate by using both metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) was successfully demonstrated with a J_{th} of 900 A/cm^2 at room temperature (RT) [7]. However, the lasing wavelength was around 1.0 µm, which is shorter than that required for the telecommunication band of 1.3 µm. Although RT 1.3-µm emission has been demonstrated for InAs/Sb:GaAs QDs on Si substrate using low-pressure MOCVD, the photoluminescence (PL) spectrum is much broader and weaker than that of the reference sample grown on GaAs substrate [14]. Moreover, there has been no report yet on the realisation of 1.3-µm QD lasers by direct epitaxial growth of III-V compounds on Si substrates.

In the present work, we first optimized the growth temperature of the GaAs nucleation layer on Si substrates. A standard 1.3-µm InAs/InGaAs dot-in-a-well (DWELL) laser structure was then directly grown on Si substrate with the use of optimized GaAs nucleation temperature. Our device exhibits ground-state lasing at 1.302 µm by electrical carrier injection, with J_{th} of 725 A/cm^2 at room temperature (RT). QD laser operation is achieved for heatsink temperatures up to 42 °C, with a characteristic temperature, T_0, of ~44 K between 20 °C and 42 °C.

2. Effects of the growth temperature on the GaAs nucleation layer on Si substrate

InAs/GaAs QD samples were fabricated on Si substrates by solid-source MBE. The schematic layer structure is illustrated in Fig. 1. Phosphorus-doped (100)-orientated Si substrates with 4° offcut towards the [110] planes were used in our experiments. Oxide desorption was performed by holding the Si substrate at a temperature of 900 °C for 10 minutes. The Si substrate was then cooled down for the growth of a 30-nm GaAs nucleation layer with a low growth rate of 0.1 monolayers (ML)/s. The growth of the GaAs nucleation layer was studied for growth temperatures of 380 °C, 400 °C, and 420 °C. An additional 970-nm GaAs layer was grown with a high growth rate of 0.7 ML/s at high temperature. InGaAs/GaAs dislocation filter layers, consisting of two repeats of a five-period (10-nm $In_{0.15}Ga_{0.85}As$/10-nm GaAs) superlattices (SPLs) and 400-nm GaAs, were used [8,9]. Finally 1-µm SPL layers of alternating 5-nm GaAs/5-nm $Al_{0.4}Ga_{0.6}As$ layer completed the III-V buffer layers. Five InAs/InGaAs DWELL layers were then grown at optimized conditions as on GaAs substrates, with each layer consisting of 3.0 MLs of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and capped by 6 nm of $In_{0.15}Ga_{0.85}As$ [15]. 45-nm GaAs barriers separated the five DWELLs. The growth temperature was 580 °C for GaAs, and 510°C for the In-containing layers. Atomic force microscopy (AFM) measurements were performed on uncapped samples in which the growth was halted after the formation of the first-layer InAs QDs. A typical AFM image for the

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sample with the initial GaAs nucleation layer grown at 400 °C is shown in the inset of Fig. 2, from which a QD density of 4.3×10^{10} cm^{-2} is obtained.

Fig. 1. Cross-sectional schematic of fabricated InAs/InGaAs dot-in-a-well structure on Si substrate.

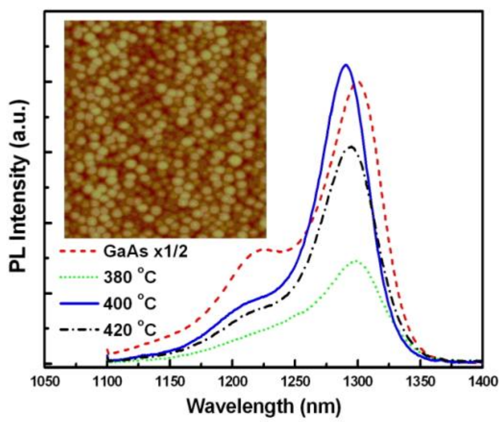

Fig. 2. RT PL spectra of InAs/GaAs QDs grown on Si substrates with different growth temperatures for the initial GaAs nucleation layer. The RT PL spectrum of InAs QDs grown on GaAs substrate is also shown as a reference. The inset shows a 1 × 1 µm^2 AFM image of InAs/GaAs QDs grown on Si substrate.

Figure 2 compares RT PL spectra of InAs/GaAs QDs grown on Si substrate with different GaAs nucleation temperatures and with a reference QD sample grown on GaAs substrate. The QDs yield RT emission at around 1.3 µm with full width at half maximum (FWHM) of ~30 meV for all the samples shown in Fig. 2. These PL linewidths obtained from InAs/GaAs QDs on Si substrates are much narrower than that of ~53 meV reported for InAs/Sb:GaAs QDs grown on a Si substrate by MOCVD [14], and it is comparable to the values obtained for GaAs-based 1.3-µm InAs QDs [15]. Of considerable significance is that the PL intensity of the InAs/GaAs QD ground-state transaction on Si is strongly dependent on the growth temperature of the initial GaAs nucleation layer. The strongest PL intensity for InAs/GaAs QDs on Si substrate is obtained from the sample with initial GaAs growth at 400 °C, and it is more than a half that of InAs QDs grown on GaAs substrate. It should be mentioned that the InAs QDs grown on GaAs substrate were grown under optimized conditions and represents

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very high optical quality as the QD laser diode based on identical growth parameters gives an extremely low J_{th} and high output power at RT [11,16].

To understand the effect of the growth temperature of the initial GaAs nucleation layer on the optical properties of InAs/GaAs QDs on Si substrate, transmission electron microscopy (TEM) measurements were performed to compare the structural properties of GaAs/Si interfaces with different GaAs nucleation temperatures, as shown in Fig. 3. The defects are generated at the GaAs/Si interface for all the samples shown in Fig. 3 due to the mismatch between GaAs and Si. Most defects are confined within 50 nm of GaAs/Si interface while some propagate into the III-V buffer layers. The density of defects propagating into the GaAs buffer is strongly dependent on the GaAs nucleation temperature with the lowest density of defects at 400 °C, and hence the strongest PL intensity for Si-based InAs/GaAs QDs observed in Fig. 2.

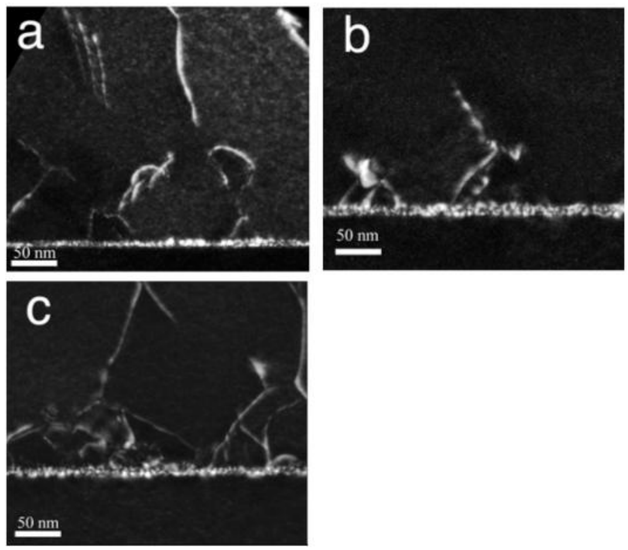

Fig. 3. Cross-sectional TEM images of GaAs/Si interface for the initial GaAs nucleation layer grown at (a) 380 °C, (b) 400 °C, and (c) 420 °C.

3. Crystal growth and fabrication of broad-area InAs/GaAs QD lasers

A 5-layer InAs/InGaAs DWELL laser structure on Si substrate was fabricated with the use of the optimised GaAs nucleation temperature of 400 °C and on Si-doped III-V buffer layers. The III-V buffer layer is similar to that used for studying the effects of the GaAs nucleation layer and consisted of the following layer sequence: GaAs buffer layer, InGaAs/GaAs dislocation filter layers, and GaAs/AlGaAs superlattice layers. The 5-layer InAs/InGaAs DWELL structure was grown at the center of an undoped 150-nm GaAs/AlGaAs waveguide layer with n-type lower and p-type upper cladding layers consisting of 1.5-μm $Al_{0.4}Ga_{0.6}As$ deposited at 610 °C. A 300-nm p^+-GaAs contact layer completed the growth. Broad-area 50-μm stripe lasers with cleaved facets were then formed by applying Ti/Au on the top and Cr/Au on the bottom of the structure. Devices of 3-mm length were bar-tested, being directly probed without any mounting and bonding.

4. Results and discussion

Figure 4 shows the light output against current characteristics of a fabricated device at RT. Laser characteristics were measured in pulsed mode using a pulse width of 0.1 μs and duty cycle of 0.01%. The measured output power is 26 mW at an injection current density of 1.2 kA/cm^2, with no evidence of power saturation up to this current density. The RT J_{th} is 725 A/cm^2, which is lower than the previously reported values of 900 A/cm^2 for a 1.02-μm

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InGaAs/GaAs QD laser directly grown on Si substrate [7]. Note that this device was processed with as-cleaved facets. The use of high-reflection (HR) coating on the facets in future studies will further decrease J_{th} [16]. The inset in Fig. 4 shows the laser optical spectrum above threshold, in which RT lasing at 1.302 μm is observed.

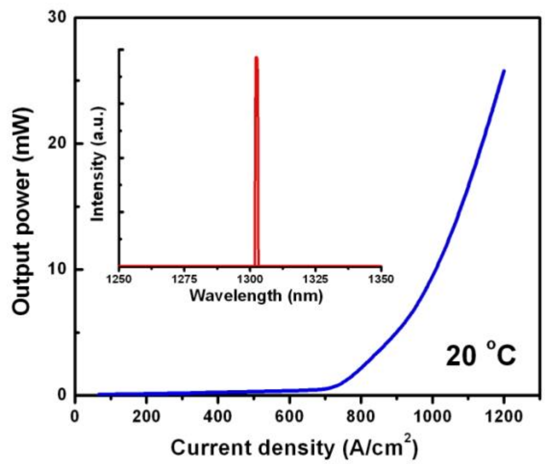

Fig. 4. Light output against current characteristic for InAs/GaAs quantum-dot laser on Si substrate under pulsed conditions at room temperature. The inset shows the laser optical spectrum above threshold.

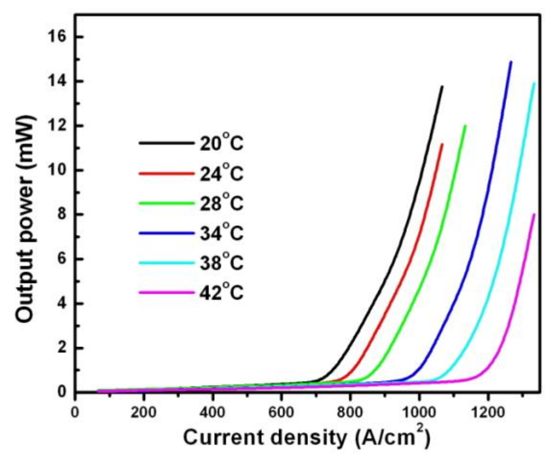

Fig. 5. Light output against current characteristic for InAs/GaAs quantum-dot laser on Si substrate at various operating temperatures.

Figure 5 shows the output power for a Si-based InAs/GaAs QD laser at various operation temperatures, ranging from 20 °C to 42 °C. This QD laser has a 42 °C maximum lasing temperature with a characteristic temperature T_0 of 44 K. Note that generally 1.3-μm InAs/GaAs QD lasers show poor T_0 in the range of 35 K - 60 K around RT [17]. The temperature stability of 1.3-μm InAs/GaAs QD lasers on Si could be significantly enhanced by using p-type modulation doping of the QDs, which is a well established technique for dramatically increasing the value of T_0, even up to $T_0 \sim \infty$ for GaAs-based QD lasers [10].

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5. Summary

We have demonstrated the first operation of 1.3-μm InAs/GaAs QD lasers epitaxially grown on Si substrates by molecular beam epitaxy. The GaAs nucleation temperature on the Si substrate has been first optimized for obtaining high PL intensity of 1.3-μm InAs/GaAs QDs grown on Si substrates. RT lasing at 1.302 μm has been achieved 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 with as-cleaved facets. This study is an essential step toward the monolithic integration of long-wavelength InAs/GaAs QD lasers on Si substrates, as well as for the creation of other III-V devices on Si.

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