Optimisation of 1.3-µm InAs/GaAs Quantum-Dot Lasers Monolithically Grown on Si Substrates

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Abstract. We present a study of 1.3-µm InAs/GaAs quantum dot lasers monolithically grown on Si substrates by molecular beam epitaxy. We focused on the optimization of III-V buffer layers epitaxy grown on Si substrates, which includes the nucleation layers and the dislocation filter layers. The effect of growth temperature of GaAs nucleation layer has been investigated. Additionally, InAlAs/GaAs and InGaAs/GaAs strained layer superlattices (SLSs) are compared as dislocation filter layers. Our results show the optimization of III-V buffer layers grown on Si is critical to achieve high performance quantum-dot lasers. An optimised 1.3-µm board-area laser has been demonstrated with a low threshold current density of 194 A/cm² and output power of 77 mW at room temperature.

1. Introduction

Si photonics has attracted much attention currently. Although in the last 20 years, intensive studies have focused on Si-based laser, which is the last missing element of Si photonics, efficient Si laser is not yet developed due to the indirect band-gap of Si [1]. Si Raman lasers, Si hybrid lasers, and III-V and Ge lasers monolithically grown on Si substrates have been demonstrated [2-6]. Among these efforts, the integration of III-V lasers monolithically on Si substrate is considered to be a promising solution to obtain efficient light sources on the Si platform in the near future.

The major issues of direct epitaxy of III-V materials on Si substrates are the formation of anti-phase boundary (APB) due to the polar/non-polar nature of III-V and group IV materials, and the threading dislocations (TDs) caused by lattice mismatch between GaAs and Si (4.1%). Also the difference in thermal expansion coefficient between III-V materials and Si substrates presents further challenges in the direct combination of these two material systems. The design of buffer layers has been proved to play a key role in obtaining high quality III-V materials on Si substrates [7]. The two-step GaAs buffer layer grown at low temperature could eliminate the APB and stop most of the TDs [7]. SLSs is also an effective method to reduce the TDs propagating in the semiconductor materials including AlGaN/GaN SLSs on sapphire [8], InGaAs/GaAs SLSs on Si [9] etc. III-V Quantum dot (QD) lasers have been demonstrated with very low threshold current, high operating temperature, high characteristic temperature, and high output power lasers in communication wavelengths (1.3 and 1.5 µm) due to its delta-function density of states [10, 11]. Furthermore, QD device is less sensitive to defects [12]. The recent demonstrations of high-performance 1.3-µm InAs/GaAs QD lasers on Ge and Ge/Si substrates
have made a significant progress towards solving monolithic integration of III-V emitters on Si substrates. However, the direct epitaxy of III-V on Si substrates still needs to be further improved [3, 12, 13]. In this paper, the III-V buffer growth on Si substrates has been studied, including the optimization of GaAs nucleation layers and the investigation of InGaAs/GaAs and InAlAs/GaAs SLSs as dislocation filter layers (DFLs). 1.3-µm InAs/GaAs quantum dot lasers directly grown on Si substrates have been demonstrated with a low threshold current density of 725 A/cm² with InGaAs/GaAs DFLs and 194 A/cm² with InAlAs DFLs, respectively.

2. Optimisation of GaAs nucleation layer grown on Si substrate

The Si substrate has been de-oxidized by holding it at 900 °C for 10 minutes and then cooled down to grow the first 30-nm GaAs nucleation layer. The GaAs nucleation layer has been investigated at temperatures of 380, 400 and 420 °C, and additional 970-nm GaAs buffer layer has been grown with higher temperatures. Test samples with 5 layers of InAs/GaAs quantum dots-in-a-well (DWELL) [14] have been grown to investigate the effects of GaAs nucleation temperatures.

Figure 1. Cross-sectional TEM images of GaAs grown on Si substrates with different nucleation temperatures: (a) 380 °C, (b) 400 °C, and (c) 420 °C.

Transmission electron microscopy (TEM) studies were used to study the effects of the GaAs nucleation temperature on Si substrates. It clearly shows the GaAs with 400°C has the lowest threading dislocation density, as shown in Figure 1. The defects, mostly TDs, are mainly due to the misfit between GaAs and Si (~4%). The TDs easily propagate through buffer layer into active region, which could be non-radiative combination centers and increase threshold current density [15]. In Figure 1, the first 30nm GaAs nucleation layer is full of defects which generated from the GaAs/Si interface. However, most of defects are strongly confined in the nucleation layer and only few are able to propagate to the subsequent buffer layer. The effects of GaAs nucleation layer was further studied by photoluminescence (PL) study, as shown in Figure 2. The samples have been excited from a 532-nm diode-pumped solid-state laser with 94-mW power at room temperature. Figure 2 shows the one grown at 400°C has the strongest PL emission at room temperature, which is consistent with TEM results shown in Figure 1.

3. The reduction of threading dislocation by dislocation filter layers

In order to reduce the propagation of TDs into active region, InAlAs/GaAs and InGaAs/GaAs DFLs have been both studied in this work. Five layers of InAlAs/GaAs SLSs or InGaAs/GaAs SLSs with 3 repeats separated by GaAs spacing layers have been grown on an optimised GaAs buffer layer. 5-layers of typical InAs/InGaAs dot-in-a-well (DWELL) structures have been grown to compare the effectiveness of DFLs [16]. The room-temperature PL shown in Figure 3, shows a stronger emission for the sample with InAlAs/GaAs SLSs around 1300 nm. The relative lower emission for the sample with InGaAs/GaAs SLSs indicates the worse crystal quality than the one with InAlAs/GaAs SLSs. The spontaneously emission of quantum dots is high relied on the DFLs effectiveness, because the threading dislocation could kill the minority-carriers easily [17].
Figure 2. Room-temperature PL spectra of InAs/GaAs QDs grown on Si substrates with different initial GaAs nucleation temperatures from 380 to 420°C.

Figure 3. Room temperature PL spectra of InAs/GaAs quantum dots grown on Si substrate with InGaAs/GaAs SLSs and InAlAs/GaAs SLSs as DFLs.

Atomic force microscopy (AFM) and TEM have been used to examine the quality of quantum dots. Figure 4(a) and (b) show the uncapped InAs/GaAs QDs grown on Si substrate with InGaAs/GaAs and InAlAs/GaAs DFLs separately. It obviously shows the InAlAs/GaAs DFLs provide better dot size distribution than InGaAs/GaAs DFLs. In addition, Figure 4(b) is free of quantum dot coalescence but Figure 4(a) is not, which means the InAlAs/GaAs DFLs provides better GaAs matrix for InAs/InGaAs DWELL structures than the InGaAs/GaAs DFLs. Transmission electron microscopy has been used to examine the defects propagating within GaAs buffer and effects of DFLs. Figure 5(a) shows most of the TDs have been stopped by two sets of DFL layers. Most of TDs are confined below the first layer of SLSs. Only a few are able to be survived after the second set of InAlAs/GaAs SLSs. InAlAs/GaAs SLSs are shown to be effective enough to eliminate TDs and there is free of defect in the active region, as shown in Figure 5(b).
Figure 4. AFM images (1×1 μm²) of InAs/GaAs QDs grown on Si substrates with (a) InGaAs/GaAs DFLs; (b) InAlAs/GaAs DFLs.

Figure 5. Cross-sectional TEM images of (a) 3 repeats of 20-layers InAlAs/GaAs SLSs and (b) active region which consists of 5 layers of InAs/GaAs QDs capped with InGaAs.

4. Result and discussions

The laser devices have been studied. 1-μm GaAs buffer layer has been deposited on Si substrates similar to the test samples. InGaAs/GaAs and InAlAs/GaAs DFLs have both tested in laser structures for comparison. Both DFLs have 4 repeats of SLSs separated by 400-nm GaAs space layer. 1.5-μm Al₀.₄Ga₀.₆As cladding layers have been grown on top and bottom of the active region with n and p doping separately. The active region is a typical DWELL structure with five layers of InAs QDs. 300-nm p-type GaAs contact layer is deposited on the top of laser structure. The samples have been fabricated into board-area lasers with 3.0-mm cavity. The laser with InGaAs/GaAs DFLs structure has a maximum operating temperature of 42°C. Figure 6 shows that the threshold current density of InAs/GaAs quantum dot lasers with InGaAs/GaAs SLSs DFLs is 725 A/cm² at 20°C. In comparison, the laser with InAlAs/GaAs DFLs shows a relatively low threshold current density of 196 A/cm² at room temperature and the maximum operating temperature is 85°C (Figure 7). The characteristic temperature ($T_0$) is 44 K between operating temperature from 20 to 45°C for the laser with InGaAs/GaAs DFLs and is 46 K between 20 to 85°C for the one with InAlAs/GaAs DFLs. The poor $T_0$ observed for both devices is due to the carrier escape in the heterostructure when the laser is heated up. The future work will be the optimisation of characteristic temperature by using p-type modulations.
Figure 6. InAs/GaAs quantum dot lasers grown on Si substrate with InGaAs/GaAs DFLs: Output power against current density at various temperatures from 20 to 42°C.

![Graph showing output power against current density at various temperatures.](image)

Figure 7. InAs/GaAs quantum dot lasers grown on Si substrate with InAlAs/GaAs DFLs: Output power against current density at various temperatures from 20 to 85°C.

**5. Conclusion**

We reported the optimisation of growing InAs/GaAs QD lasers on Si substrates. It has been shown that the growth temperature of the GaAs nucleation layer plays a critical role in material quality of the arsenide layers grown on Si substrates. We also compared the effectiveness of InAlAs/GaAs and InGaAs/GaAs SLSs as DFLs and show that InAlAs/GaAs SLSs provides better crystal quality as confirmed by PL and TEM measurements. 1.3-μm InAs/GaAs QD lasers directly grown on Si substrate with both InGaAs/GaAs and InAlAs/GaAs DFLs have been successfully demonstrated and compared. The significant improvement in the operating temperature and threshold current density has been demonstrated for the lasers with InAs/GaAs DFLs. The laser device shows high output power around 80 mW and low threshold current density of 196 A/cm². As-cleaved laser is able to operate at maximum temperature of 85°C under pulsed mode.
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