Room-Temperature Operation of Vertical-Cavity Surface-Emitting Laser on Si Substrate

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We have demonstrated room-temperature pulsed operation of an AlGaAs/GaAs vertical-cavity surface-emitting laser (VCSEL) grown on Si substrate using metalorganic chemical vapor deposition. The VCSEL on Si consists of a single quantum well active layer and a 20-pair AlAs-GaAs quarter-wave reflector stack. The measured reflectivity of the 20-pair AlAs-GaAs reflector stack is 93% at the wavelength of 860 nm. The VCSEL on Si exhibits a threshold current of 79 mA and a threshold current density of 4.9 kA/cm² under room-temperature pulsed condition.

1. INTRODUCTION

The fabrication of lasers on Si substrates has been studied in recent years because this technology is very promising in the realization of optoelectronic integrated circuits (OEIC's). Previous studies of lasers grown on Si have focused on the edge-emitting lateral-cavity structures. Although room-temperature continuous-wave operation of GaAs-based lasers on Si has been reported, reliable GaAs-based lasers on Si have been hindered by the high density dislocation and strain, which cause a rapid degradation.⁴⁻⁵

Recently, vertical-cavity surface-emitting lasers (VCSEL's) on Si have been attracting increasing interest because of their advantages over edge-emitting lasers, such as the potential for wafer scale testing, easy of two-dimensional array fabrication, and possibility of monolithic integration with other optical or electronic devices.⁶⁻⁸ Moreover, the strain and dislocations can be reduced in the VCSEL's with small active volume. In this study, we demonstrate the room-temperature pulsed operation of AlGaAs/GaAs VCSEL on Si.

2. EXPERIMENTAL

The VCSEL structure was grown on an n⁺-Si substrate oriented 2° off (100) toward [110] using metalorganic chemical vapor deposition (MOCVD) at atmospheric pressure. The AlGaAs/GaAs VCSEL structure was grown on Si at 750 °C by the two-step growth technique. Details about epitaxial growth have been described previously.⁹ The structure consists of a 0.85-μm-thick n⁺-GaAs buffer layer, a 20-pair of an n⁺-AlAs (71 nm)-GaAs (59 nm) quarter-wave reflector stack, a 0.46-μm-thick lower n-Al₀.₇Ga₀.₃As cladding layer, a 70-nm-thick lower n-Al₀.₃Ga₀.₇As confining layer, a 9-nm-thick GaAs active layer, a 70-nm-thick upper p-Al₀.₃Ga₀.₇As confining layer, a 0.34-μm-thick upper p-Al₀.₇Ga₀.₃As cladding layer, and an 80-nm-thick p⁺-GaAs contact layer. In order to reduce the threading dislocation density, thermal cycle annealing was performed five times by varying the substrate temperature between 350 °C and 850 °C during the n⁺-GaAs layer growth.

Au-Sb/Au was used for the contact on the n⁺-Si substrate. Nonalloyed Au-Zn/Au of 40x40 μm square, which is used for the top mirror and the electrical contact, was formed by the photore sist patterning and the lift-off technique. Mesa etching or ion implantation is not performed to provide the lateral current confinement. The devices were mounted junction up on a sample holder and tested under pulsed operation at room temperature using a current source with 100 ns pulselwidth. The cross-sectional structure of the VCSEL on Si was observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The dark spot density (DSD) was measured by electron-beam-induced current (EBIC) method.

3. RESULTS AND DISCUSSION

Figure 1 shows a cross-sectional SEM micrograph of the overall AlGaAs/GaAs VCSEL structure grown on Si. A cross-sectional TEM micrograph of the AlAs-GaAs quarter-wave reflector stack in the VCSEL grown on Si is also shown in Fig. 2. Smoothness and uniformity are clearly seen in AlAs-GaAs quarter-wave reflector stack. Previous study has indicated that the AlAs-GaAs quarter-wave reflector stack can be effective in bending dislocations.⁷ As shown in Fig. 2, however, dislocation bending is not observed in the AlAs-GaAs quarter-wave reflector stack. Many
dislocations propagate into the active layer. This VCSEL on Si, which was grown with the thermal cycle annealing and the AlAs-GaAs quarter-wave reflector stack, showed the DSD of 2.5x10^7 cm^-2. This value is almost the same value of the sample without the AlAs-GaAs quarter-wave reflector stack. This result also indicates that the AlAs-GaAs quarter-wave reflector stack can not be effective in bending the threading dislocations because there is less mismatch in the lattice constant for the AlAs-GaAs layers.

The calculated and measured reflectivities of the 20-pair AlAs-GaAs quarter-wave reflector stack are shown in Fig. 3. The measured reflectivity is above 90% at the wavelength region between 820 nm and 870 nm, and 93% at the wavelength of 860 nm. A relatively lower reflectivity is probably due to the microroughness in the surface morphology. It is well known that the GaAs/Si grown by the two-step growth technique exhibits the microroughness in the surface morphology. We have found that the microroughness is caused by the hillocks and depressions with a different size using scanning tunneling microscope. The reflectivity will be increased by use of the AlGaAs/AlGaP intermediate layers, which contribute to the specular surface morphology in the GaAs/Si. A higher reflectivity will be also expected by increasing the number of pair. However, a thicker epitaxial layer can not be grown on Si due to the formation of microcracks. The top mirror has the reflectivity of 60% for the alloyed and 96% for the nonalloyed Au-Zn/Au. A higher reflectivity of the nonalloyed Au-Zn/Au is caused by the smooth morphology due to the lack of thermal annealing.

The turn-on voltage and the series resistance are 1.3 V and 22 Ω. These values are comparable to those of the conventional edge-emitting lasers on Si. Figure 4 shows the room-temperature pulsed light versus current (L-I) characteristic of the VCSEL on Si. The threshold current ($I_{th}$) and the threshold current density ($J_{th}$) are 79 mA and 4.9 kA/cm², respectively. The VCSEL on Si with the pulsed $I_{th}$ of 125 mA ($J_{th}$=70.8 kA/cm²) has been reported by another group. Compared with the previously reported result, a remarkable improvement has been achieved in our VCSEL on Si.

Fig. 1. Cross-sectional SEM micrograph of the overall AlGaAs/GaAs VCSEL structure grown on Si by MOCVD. The active layer consists of Al_{0.3}Ga_{0.7}As/GaAs SQW.

Fig. 2. Cross-sectional TEM micrograph of the AlAs-GaAs quarter-wave reflector stack grown on Si by MOCVD. The thicknesses of AlAs and GaAs layers were 71 nm and 59 nm, respectively.

Fig. 3. Calculated and measured reflectivities of the 20-pair AlAs-GaAs quarter-wave reflector stack grown on Si by MOCVD. The thicknesses of AlAs and GaAs layers were 71 nm and 59 nm, respectively.
PULSED ; 300 K
VCSEL on Si

\[ I_0 = 79 \text{ mA} \]
\[ J_m = 4.9 \text{ kA/cm}^2 \]

Fig. 4. Room-temperature pulsed L-I characteristic of the VCSEL grown on Si by MOCVD.

4. CONCLUSIONS

We have demonstrated the room-temperature pulsed operation of the AlGaAs/GaAs VCSEL on Si with the 20-pair AlAs-GaAs quarter-wave reflector stack. Nonalloyed Au-Zn/Au of 40x40 μm square was also used for the top mirror and the electrical contact. The measured reflectivity of the 20-pair AlAs-GaAs quarter-wave reflector stack is 93% at the wavelength of 860 nm. TEM observation indicates that the AlAs-GaAs quarter-wave reflector stack can not be effective in bending the threading dislocations because there is less mismatch in the lattice constant for the AlAs-GaAs layers. The threshold current and the threshold current density are 79 mA and 4.9 kA/cm², respectively, which are a remarkable improvement over previously reported results. The VCSEL’s on Si are promising for both optical interconnections and optical computing.

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REFERENCES


