Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 1032-1034



# 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/cm$^2$ 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).[1-3] 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-$Al_{0.7}Ga_{0.3}As$ cladding layer, a 70-nm-thick lower n-$Al_{0.3}Ga_{0.7}As$ confining layer, a 9-nm-thick GaAs active layer, a 70-nm-thick upper p-$Al_{0.3}Ga_{0.7}As$ confining layer, a 0.34-μm-thick upper p-$Al_{0.7}Ga_{0.3}As$ 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 photoresist 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 pulsewidth. 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 $2.5 \times 10^7$ $cm^{-2}$. 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.

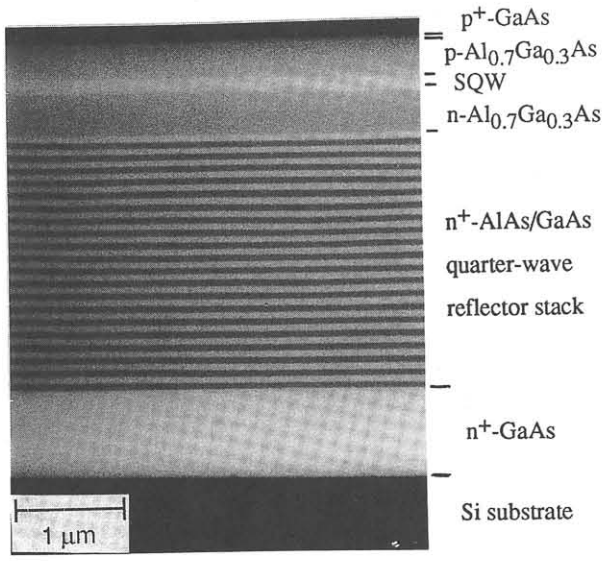


Fig. 1. Cross-sectional SEM micrograph of the overall AlGaAs/GaAs VCSEL structure grown on Si by MOCVD. The active layer consists of $Al_{0.3}Ga_{0.7}As$/GaAs SQW.

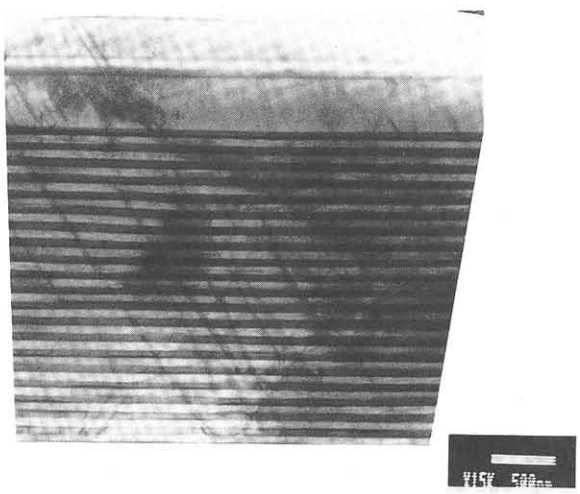

Fig. 2. Cross-sectional TEM micrograph of the AlAs-GaAs quarter-wave reflector stack grown on Si by MOCVD. The thicknesses of AlAs and GaAs layers were 71 nm and 59 nm, respectively.

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.[10] The reflectivity will be increased by use of the AlGaAs/AlGaP intermediate layers, which contribute to the specular surface morphology in the GaAs/Si.[10] 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/$cm^2$, respectively. The VCSEL on Si with the pulsed $I_{th}$ of 125 mA ($J_{th}$=70.8 kA/$cm^2$) has been reported by another group.[7] Compared with the previously reported result, a remarkable improvement has been achieved in our VCSEL on Si.

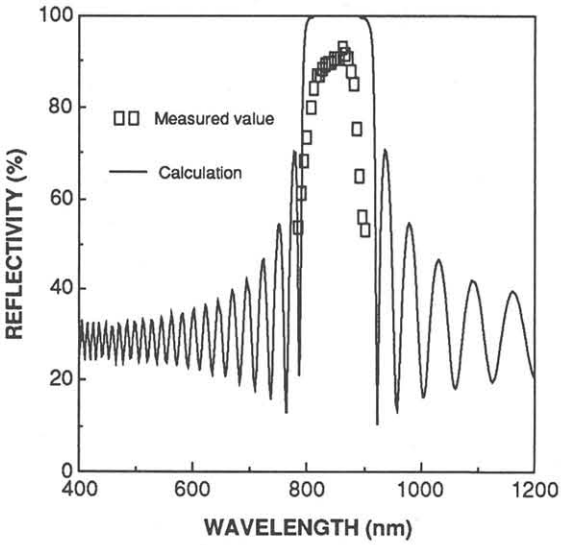


Fig. 3. Calculated and measured reflectivities of the 20-pair AlAs-GaAs quarter-wave reflector stack grown on Si by MOCVD. The thicknesses of AlAs and GaAs layers were 71 nm and 59 nm, respectively.

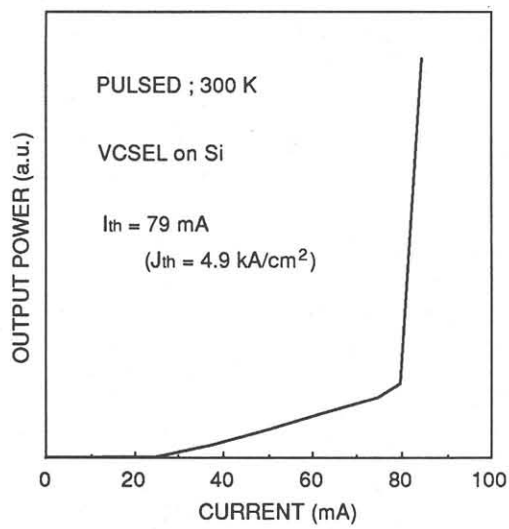


Fig. 4. Room-temperature pulsed L-I characteristic of the VCSEL grown on Si by MOCVD.

## 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/cm$^2$, respectively, which are a remarkable improvement over previously reported results. The VCSEL's on Si are promising for both optical interconnections and optical computing.

## ACKNOWLEDGMENT

The authors would like to acknowledge Dr. Y. Nishi (Nagoya Municipal Industrial Research Institute) for SEM observation, and Mr. A. Oda (Canare Electric Co., Ltd.) for TEM observation.

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