

Low-threshold continuous-wave room-temperature operation of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ single quantum well lasers grown by metalorganic chemical vapor deposition on Si substrates with SiO_2 back coating

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We demonstrate the first room-temperature low-threshold continuous-wave (cw) operation of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ single quantum well (SQW) heterostructure lasers grown by metalorganic chemical vapor deposition (MOCVD) on Si substrates using techniques of SiO_2 back coating and thermal cycle annealing. The all-MOCVD-grown SQW lasers on GaAs/Si with etch pit density of $1.5 \times 10^7 \text{ cm}^{-2}$ have threshold current as low as 55 mA (1.41 kA/cm^2) under cw at room temperature. The SiO_2 back coating is effective to obtain excellent current-voltage characteristics. Thermal cycle annealing is also found to improve the crystallinity of GaAs/Si and to contribute to room-temperature cw operation of the lasers on Si substrates.

Many efforts have been made to fabricate electronic and optical devices on GaAs/Si for the past several years. It is important for the heteroepitaxial growth of GaAs on Si substrates to fabricate these devices on the GaAs/Si because it allows the monolithic integration of Si and GaAs devices. In spite of 4.1% lattice mismatch, differences in thermal expansion coefficient and unintentional Si autodoping in the GaAs layer, metal-semiconductor field-effect transistors (MESFETs), high-electron mobility transistors (HEMTs), and laser diodes have been fabricated on the GaAs/Si grown by metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) technique.¹⁻³ However, all of the continuous-wave (cw) room-temperature operating lasers on the GaAs/Si have been grown by a combination of MBE and MOCVD techniques.³ In this letter, we demonstrate the first all-MOCVD-grown low-threshold cw room-temperature operating $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ single quantum well (SQW) lasers on Si substrates using techniques of SiO_2 back coating and thermal cycle annealing. We also study the effects of SiO_2 back coating and thermal cycle annealing on the characteristics of SQW lasers on Si substrates.

Before the growth, 720-nm-thick sputtered SiO_2 films were deposited on the back of *n*-Si substrates oriented 2° off (100) towards [011]. All samples were grown by a rf-heated horizontal MOCVD reactor at atmospheric pressure using two-step growth technique. The source materials were trimethylgallium (TMG), trimethylaluminum (TMA), and pure AsH_3 . Flow rate of H_2 as a carrier gas was 6 //min. In order to study the effect of SiO_2 back coating of Si substrates on the electron concentration of GaAs layers, 4- μm -thick undoped GaAs layers were grown at 650, 700, and 750 °C on Si substrates with and without SiO_2 back coating. Carrier concentration was obtained by electrochemical capacitance voltage (*C-V*) measurement. We have also grown $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ SQW lasers at 750 °C on Si substrates with and without SiO_2 back coating. The laser consists of a 1.0- μm -thick Se-doped

($2 \times 10^{18} \text{ cm}^{-3}$) GaAs layer and twice thermal cycle annealings between 300 and 850 °C in an AsH_3 ambient, another 1.0- μm -thick of Se-doped ($2 \times 10^{18} \text{ cm}^{-3}$) GaAs layer and three times thermal cycle annealings between 300 and 850 °C in an AsH_3 ambient, a 1.0- μm -thick Se-doped ($1 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ cladding layer, a 70-nm-thick undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier layer, an 8-nm-thick undoped GaAs active layer, a 70-nm-thick undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier layer, a 1.0- μm -thick Zn-doped ($1 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ cladding layer, and an 80-nm-thick Zn-doped ($1 \times 10^{19} \text{ cm}^{-3}$) GaAs cap layer. The thermal cycle annealing was performed by interrupting the growth. The thermal cycle annealing was as follows. The temperature of the sample was lowered to 300 °C from the growth temperature and then raised to 850 °C. After repeating this thermal cycle, the annealing was performed at 850 °C for 20 min and the sample was kept at the growth temperature of 750 °C. After the growth, 0.1- μm -thick SiO_2 films were sputtered and 10- μm -wide stripe windows were opened by chemical etching. After the substrates were lapped off down to about 100 μm thickness, Au-Zn/Au and Au-Sb/Au ohmic electrodes were formed by vacuum evaporation on the *p*-GaAs cap layer and *n*-Si substrate, respectively. The evaporated ohmic electrodes were annealed at 420 °C for 2 min in N_2 ambient. The samples were cleaved into 300 $\mu\text{m} \times 390 \mu\text{m}$ chips. The chip was mounted on a Cu heat sink with *p*-side up configuration. For comparison, an identical laser structure was fabricated on a GaAs substrate.

Figure 1 shows the growth temperature dependence of electron concentration of the GaAs layers grown on Si substrates with and without SiO_2 back coating. The electron concentration of the GaAs layer grown on Si substrate without SiO_2 back coating increases in the range of 10^{15} – 10^{17} cm^{-3} at higher growth temperature. For the GaAs layer on Si substrate with it, however, the electron concentration is as low as $1 \times 10^{15} \text{ cm}^{-3}$ between 650 and 750 °C. For the GaAs layer on Si substrate without SiO_2 back

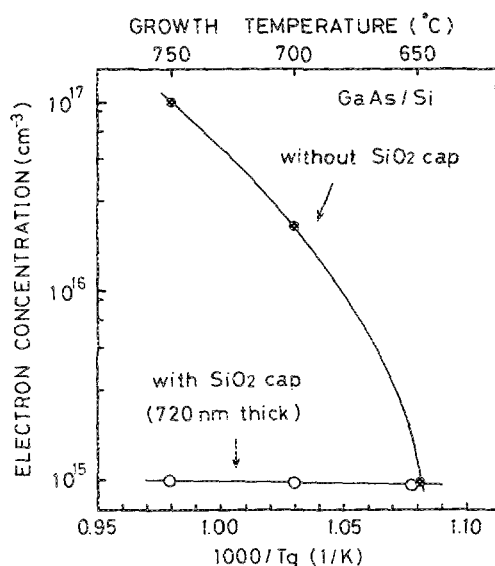


FIG. 1. Growth temperature dependence of electron concentration of GaAs layers on Si substrates with and without SiO₂ back coating. The thicknesses of SiO₂ back coating and GaAs layer are 720 nm and 4 μ m, respectively.

coating, the increase of electron concentration at higher growth temperature is due to the enhanced Si incorporation in the GaAs layer.⁴ Another important effect of SiO₂ back coating has been obtained in current-voltage (*I-V*) characteristics of the SQW lasers grown on Si substrates. The *I-V* characteristics of the SQW lasers on Si substrates with and without SiO₂ back coating are shown in Fig. 2. The lasers on SiO₂ back coated Si substrates show sharp turn-on, while the lasers on Si substrates without SiO₂ back coating show gradual turn-on. This result may be due to the conversion of *p*-type cladding layer to *n*-type.⁵ Above results indicate that SiO₂ back coating of Si is effective to control the doping and obtain the excellent *I-V* characteristic of the lasers on Si substrates.

Figure 3 shows the injection current versus light output power (*I-L*) characteristics of the Al_{0.3}Ga_{0.7}As/GaAs SQW lasers grown on GaAs and Si substrates. The laser on GaAs substrate has the cw threshold current (*I*_{th}) of 32

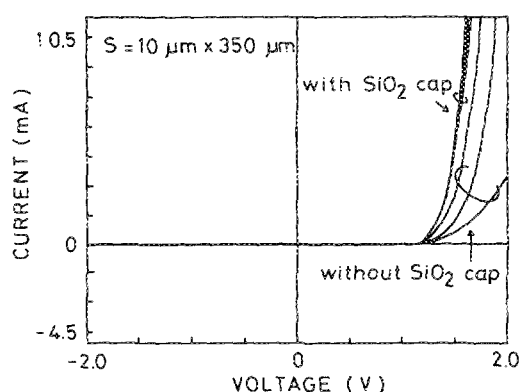


FIG. 2. *I-V* characteristics of the SQW lasers grown on Si substrates with and without SiO₂ back coating. The contact area is about 10 μ m \times 350 μ m.

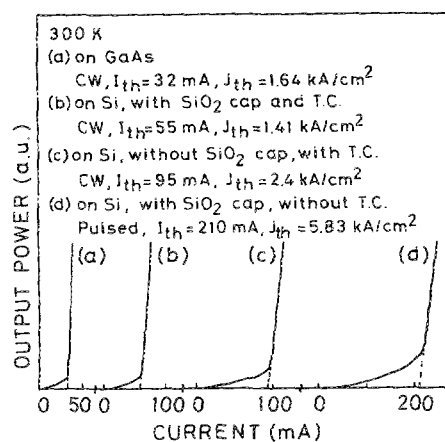


FIG. 3. Room-temperature *I-L* characteristics of Al_{0.3}Ga_{0.7}As/GaAs SQW lasers on (a) GaAs substrate, (b) SiO₂ back coated Si substrate with thermal cycle annealing, (c) Si substrate without SiO₂ back coating and with thermal cycle annealing, and (d) SiO₂ back coated Si substrate without thermal cycle annealing.

mA, corresponding to the threshold current density (*J*_{th}) of 1.64 kA/cm² at room temperature. The laser on SiO₂ back coated Si substrate with thermal cycle annealings, which has the etch pit density (EPD) by molten KOH of 1.5×10^7 cm⁻², has the cw *I*_{th} as low as 55 mA (*J*_{th} = 1.41 kA/cm²) at room temperature. The single-mode operation is observed with the peak wavelength of 860 nm. The radiation from the laser is found to be dominated by the transverse electric (TE) mode,⁶ which results from a higher net gain for the TE mode than for the transverse magnetic mode. Although the laser on Si substrate has the high density of the threading dislocations, the laser has operated for several minutes under cw condition at room temperature. On the other hand, the laser with thermal cycle annealing on Si substrate without SiO₂ back coating has the *I*_{th} of 95 mA (*J*_{th} = 2.4 kA/cm²) under cw at room temperature, which is higher than that of the laser with thermal cycle annealing on SiO₂ back coated Si substrate. This is caused by the poor *I-V* characteristic discussed above. The *I*_{th} of 210 mA (*J*_{th} = 5.83 kA/cm²) under pulsed at room temperature is obtained for the laser on SiO₂ back coated Si substrate without thermal cycle annealing which has the EPD of 9.5×10^7 cm⁻². This laser could not operate under cw because of the high density of the threading dislocations.

In summary, we have shown that combination of the techniques of thermal cycle annealing and SiO₂ back coated Si contributes to all-MOCVD-grown quantum well heterostructure laser on Si substrate. By using these techniques, we have achieved room-temperature threshold current as low as 55 mA (1.41 kA/cm²) under cw for an Al_{0.3}Ga_{0.7}As/GaAs SQW laser on Si substrate.

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