Room-temperature laser operation of AlGaAs/GaAs double heterostructures fabricated on Si substrates by metalorganic chemical vapor deposition

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AlGaAs/GaAs double heterostructure laser diodes have been fabricated on Si substrates using GaP/(GaP/GaAsP) superlattice/(GaAsP/GaAs) superlattice intermediate layers grown by metalorganic chemical vapor deposition. A threshold current density at 16.5 °C and a characteristic temperature T_0 of 4.9 kA/cm^2 and 179 K respectively have been obtained for the diode on Si substrate.

The growth of GaAs on Si substrates is attracting much attention in recent years because of its wide application from optoelectronic integrated circuits to solar cells. A laser diode on Si was first reported by Windhorn *et al.*,[1] but it operated only at low temperature (77 K). We have also demonstrated the laser diode on Si at low temperature, but its operation at room temperature was not stable.[2] This letter reports the first successful room-temperature laser operation of AlGaAs/GaAs double heterostructure (DH) on Si substrate using superlattice intermediate layers grown entirely by metalorganic chemical vapor deposition (MOCVD).

The fabricated diode structure is essentially the same as that reported previously[2] and is shown in Fig. 1 along with the cross-sectional scanning electron microphotograph of the grown wafer. All the layers are grown in a normal pressure MOCVD system using trimethylgallium, trimethylaluminum, diethylzinc, AsH_3, PH_3, and H_2Se as source gases.

After annealing the Si substrate at 950 °C, a lattice-matched GaP 50 nm thick is grown at 900 °C followed by the growth of the two stages of strained layer superlattices of $(GaP/GaAs_{0.5}P_{0.5})\times 5$ and $(GaAs_{0.5}P_{0.5}/GaAs)\times 4$ at 680 °C. The thickness of each layer in the superlattices is 20 nm. Detailed growth conditions of intermediate layers and GaAs are reported elsewhere.[3,4] The total intermediate layer thickness is 0.4 μm. The usual DH structure of an *n*-GaAs (2.1 μm, $n = 2\times 10^{18}$ cm^{-3}), an *n*-$Al_{0.3}Ga_{0.7}As$ (1.5 μm, $n = 1\times 10^{18}$ cm^{-3}), an undoped GaAs (0.12 μm), a *p*-$Al_{0.3}Ga_{0.7}As$ (1.5 μm, $p = 2\times 10^{18}$ cm^{-3}), and a *p*-GaAs (0.4 μm, $p = 2\times 10^{19}$ cm^{-3}) are grown on the intermediate layers described above at 675 °C. The total epitaxial layer thickness is 6 μm. Akiyama *et al.*[5] observed cracks in GaAs layers grown directly on Si when the GaAs layer thickness is larger than 3 μm. On the other hand, no crack is seen on our as-grown wafer even on 6-μm-thick layers, showing the superiority of the intermediate layers employed here.

After growth a part of the wafer is etched to *n*-GaAs to make ohmic contact in *n*-GaAs. In this process the cracks are formed in the etched grooves along the stripe, as the etched part is thinner and more fragile than the other part of the wafer. This means that stress is still applied to the epitaxial layer even using superlattice intermediate layers, but some of the stress may be relaxed by this crack formation. These cracks do not affect the laser characteristics.

The laser mirror is fabricated by thinning the Si substrate to 50 μm and usual cleaving. As GaAs and Si have different cleavage planes, this process requires some skill. However, even when the cleaved facet of Si is not flat, the facet of the epitaxial layers tends to show a flat surface in most cases.

Figure 2 shows the current/output power relation of the fabricated laser diode at 16.5 °C, pulsed conditions. The pulse width and repetition rate are 200 ns and 1 kHz, respectively. The near field pattern is also shown in Fig. 2. Although the stripe width opened on top of the *p*-GaAs is 10

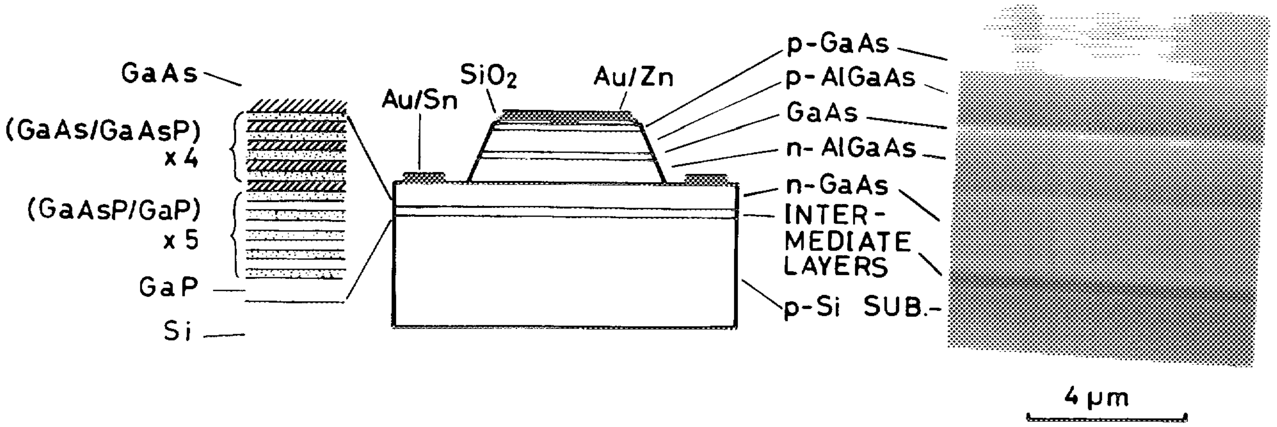

FIG. 1. Schematic cross section of the fabricated laser diode on Si and SEM microphotograph of the grown layers.

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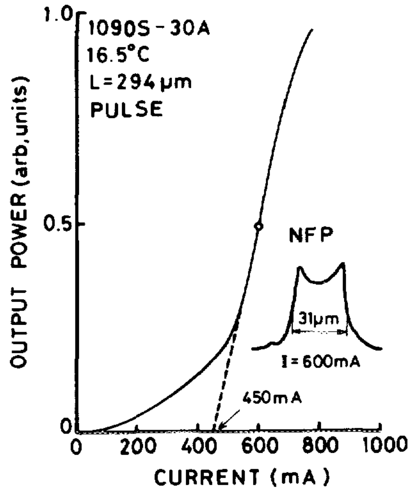

FIG. 2. Injection current-optical power relation of laser diode on Si at 16.5 °C, pulsed conditions. The cavity length is 294 μm. Near field pattern is also shown in the inset.

μm, the current spreads over 31 μm as the current flows laterally in the grown layer, and the emission from both sides of the stripe is strong. The threshold current (I_{th}) is 450 mA, which corresponds to a threshold current density of 4.9 kA/cm^2. This threshold current density is much lower than that of the recently reported laser diode on Si grown by molecular beam epitaxy in spite of the early stage of development.[6]

Figure 3 shows the lasing spectra of the diode shown in Fig. 2. At 700 mA the diode lases at two main wavelengths while it becomes single mode at 800 mA. This behavior is frequently met in broad contact lasers on GaAs substrates.

Figure 4 shows the temperature dependence of the threshold current I_{th}. The characteristic temperature T_0 of 179 K is fairly high taking into account the junction up configuration and the high threshold current density, which means a high rate of heat generation. This high value of T_0 shows the superiority of higher thermal conductance of Si compared to GaAs.

The DH lasers are grown on GaAs substrates under the same conditions as on Si for comparison. The structure is the same as described above except that the substrate is n-GaAs (100 μm thick, $n = 2\times10^{18}$ cm^{-3}). There are no intermediate layers: the n-side electrode is formed on the backside of n-GaAs substrate, the emission width is 20 μm, and the chips are mounted with p-side down configuration on a Cu heat sink. The measuring conditions are also the same as described (room-temperature pulsed conditions except the T_0 measurement). The typical threshold current density of 200-μm-long cavity devices is 0.8–1 kA/cm^2, which is about 1/6 of the lowest value on the Si substrate. The lasing wavelength is in the range 870–877 nm, which is about 5–15 nm shorter than that on the Si substrate. The spontaneous peak emission wavelength on the Si substrate is also about 10 nm longer than that on the GaAs substrate. These shifts are caused by stress applied to the layers due to the difference in thermal expansion coefficients of Si and GaAs. The T_0 value is about 120–130 K in the temperature range of -60 to 50 °C, which is lower than that on the Si substrate.

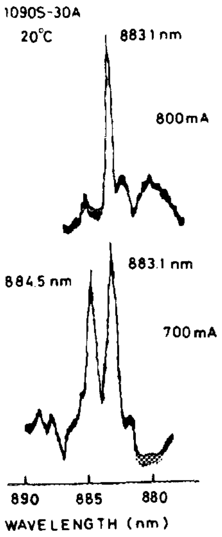

FIG. 3. Lasing spectra of the laser diode shown in Fig. 3.

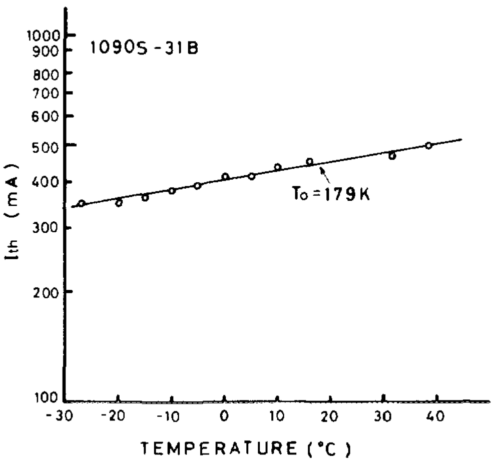

FIG. 4. Temperature dependence of the threshold current I_{th} of the laser diode on Si. The cavity length and emitting width are 255 and 30 μm, respectively.

In summary, low threshold current laser diodes on Si which operate at room temperature are demonstrated. The threshold current density at 16.5 °C and the characteristic temperature of 4.9 kA/cm^2 and 179 K respectively are obtained. The lasing characteristics will be much improved by optimizing mirror formation and device fabrication procedure. The use of n-Si substrate will also be useful as seen in the present structure where the current flows laterally in the thin n-GaAs layer resulting in high series resistance.

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