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Growth of vertical-cavity surface-emitting laser structures on GaAs (311)B substrates by metalorganic chemical vapor deposition

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Vertical-cavity surface-emitting laser (VCSEL) structures have been grown on GaAs (311)B substrates by metalorganic chemical vapor deposition. C-doped GaAs and AlAs layers with smooth surface morphology and a hole concentration of 10^{18} cm^{-3} were obtained by optimizing the growth conditions; these conditions contributed to high-quality p-type distributed Bragg reflectors (DBRs). The devices on the (311)B substrates exhibited a threshold current of 9.6 mA, voltage of 2.1 V, and maximum power of 4.1 mW at a 20 μm ϕ size; these characteristics are similar to those obtained on (100) substrates. The polarization was aligned to [233]. © *1997 American Institute of Physics.* [S0003-6951(97)01825-1]

The vertical-cavity surface-emitting laser (VCSEL) is promising for use in optical interconnections and communications.[1] In their application, the polarization direction in VCSEL oscillation should be stably maintained in order to avoid polarization induced noise.[2–4] Polarization control has been reported using anisotropic gain in VCSELs grown by molecular beam epitaxy (MBE) on GaAs (311)A and (311)B substrates,[3,4] but not yet by metalorganic chemical vapor deposition (MOCVD). One reason is that growth conditions of the epilayers on (311) substrates are largely different from those on (100) in MOCVD, and have not yet been examined. As far as our experiments, there seem to be two main problems; for (311)A, AlAs shows p-type conductivity in Si doping normally used as an n-type dopant, and for (311)B, the surface morphology of C-doped AlAs is more likely to degrade at the same growth conditions as those on (100). The first problem is more essential, so we have chosen (311)B and examined the growth condition dependences of C doping and AlAs morphology in detail. In this letter, we show the successful growth of VCSELs on (311)B substrates and discuss the VCSEL characteristics.

The structures were grown in a horizontal MOCVD reactor at 76 Torr. The growth rate was about 3 μm/h for all layers. The group III sources were trimethyl-gallium and trimethyl-aluminum, and the group V source was arsine. First, we have investigated orientation dependence of C and Si doping in the growth of GaAs and AlAs. C and Si doping sources were CBr_4 and SiH_4. 1-μm-thick GaAs and AlAs layers were grown on undoped GaAs (100), (311)A and (311)B substrates. Each AlAs layer was capped with 200 Å nondoped GaAs. The carrier concentration and mobility were measured by the van der Pauw–Hall method. The surface morphology was observed by Nomarski interference contrast microscopy. The hole concentration increased with an increasing CBr_4 flow rate on all (100), (311)A, and (311)B substrates in both GaAs and AlAs. In order to obtain a hole concentration above 10^{18} cm^{-3} for GaAs on (100), we conventionally use growth conditions such as $T_g = 650\,°C$ and V/III=60. If we apply these conditions to GaAs on (311)B, we have to increase the CBr_4 flow rate to more than 2×10^{-6} mol/min, where the etching effects of CBr_4 cannot be neglected.[5] Furthermore, in these growth conditions the AlAs surface morphology degrades. Figure 1 shows the surface morphologies of AlAs at different T_g and V/III ratios. Both increasing T_g and decreasing the V/III ratio greatly improved the surface morphology. Figure 2 shows the hole concentration in GaAs and AlAs. When T_g was increased and the V/III ratio was decreased, the hole concentration in AlAs increased; the hole concentration in GaAs decreased when T_g was increased. The improvement in AlAs morphology is explained by the AlAs diffusion, which is promoted at higher T_g and low As concentration on the surface. For DBR growth, the T_g's for the GaAs (or AlGaAs with low Al content) and AlAs (or AlGaAs with high Al content) layers must be the same, because a long growth interruption caused by the change in T_g may degrade the interface or cause the contaminants to stick. To obtain good morphology of AlAs and a hole concentration as high as 10^{18} cm^{-3} for GaAs, the V/III ratio should be decreased. The p-type GaAs/AlAs DBR grown on (311)B at $T_g = 700\,°C$ and V/III=15 was confirmed to have good surface morphology and have enough hole concentration.

The growth of n-DBR is relatively easy because n-type dopants are easily incorporated on the B face.[6] Figure 3 shows the carrier concentration in GaAs and AlAs on (311)B, (100), and (311)A. Here, $[SiH_4]/[III]$ denotes the mole fraction of SiH_4 to group III sources. The carrier type was changed in AlAs on (311)A. On the other hand, both

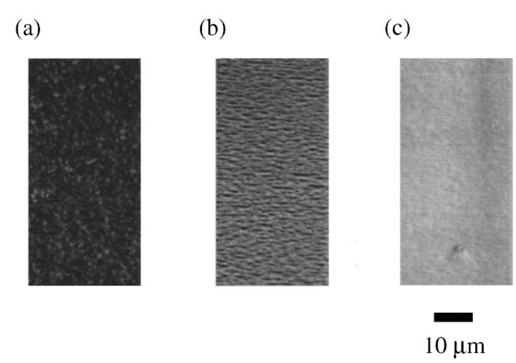

FIG. 1. Surface morphology of AlAs grown at various T_g and V/III ratios. The samples were capped with 200 Å GaAs, and the CBr_4 flow rates were fixed at 2×10^{-6} mol/min. (a) $T_g = 650\,°C$, V/III=60, (b) $T_g = 700\,°C$, V/III=60, and (c) $T_g = 700\,°C$, V/III=15.

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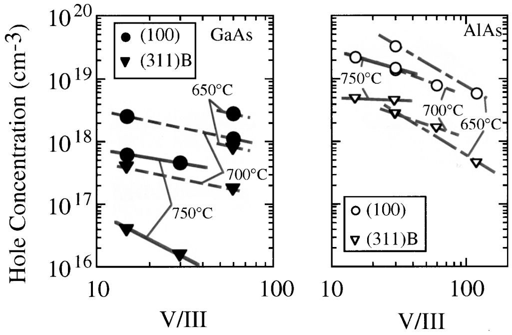

FIG. 2. Hole concentration of GaAs and AlAs on (311)B and (100) as a function of V/III ratio. The CBr_4 flow rates were fixed at 2×10^{-6} mol/min.

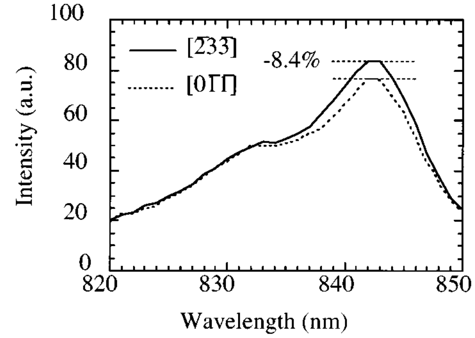

FIG. 4. PL spectrums from the $[0\bar{1}\bar{1}]$ and $[\bar{2}33]$ polarized directions.

GaAs and AlAs on (311)B were confirmed to have a carrier concentration above 10^{18} cm^{-3}. The growth temperature of 800 °C was high enough to make a smooth surface of AlAs on (311)B. Thus for n-DBR we could use growth conditions very similar to the conventional conditions ($T_g = 800$ °C, V/III$=$60).

In order to examine the active region on (311)B grown at $T_g = 750$ °C and V/III$=$60 [same at (100)], photoluminescence (PL) spectrums from the pin structure including the active region were measured. This structure consisted of three $GaAs/Al_{0.3}Ga_{0.7}As$ QWs surrounded by doped AlGaAs layers. The PL peak intensity on (311)B was 94% of that on (100) at room temperature (RT). It was confirmed that the active layers did not degrade on (311)B. The different intensity may be explained by the change in the band energy of the light hole and heavy hole. The difference in the measured peak wavelengths attributed to these two bands on (311)B was 1.6 meV larger than on (100). We also measured the orientation dependence on (311)B using a polarizer. Figure 4 shows the orientation dependence of PL spectrums along $[0\bar{1}\bar{1}]$ and $[\bar{2}33]$. The intensity along $[0\bar{1}\bar{1}]$ was 8.4% below that along $[\bar{2}33]$.

From the above results, we confirmed that the VCSEL structure can be grown on (311)B with the same quality of that grown on (100), and that it also has an anisotropic optical gain. We have fabricated top-emitting 0.85 μm 8×8 VCSEL arrays on an n-GaAs (311)B substrate. The bottom and top DBRs consisted of 37.5 and 21 $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ pairs ($Al_{0.98}Ga_{0.02}As$ is used at the layers near the active region and GaAs at the top contact layer) with heterointerface grading. Their carrier concentration is around 1×10^{18} cm^{-3}. The active region has three $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells (QWs). The cavity thickness is one wavelength long (λ-cavity). Cylindrical mesas with a 20 μm ϕ active layer were formed by Cl_2-based reactive ion beam etching. The structures were then planarized with polymide and coated by SiO_2. Au/Zn/Ni and Au/Ge/Ni were deposited for the p and n electrodes. The pitch of each element in the array was 250 μm.

Figure 5 shows the typical current-light (I-L) and current-voltage (I-V) characteristics and also shows the polarization dependence of I-L. In an 8×8 VCSEL array under cw operation at RT, the maximum power was 4.05 ± 1.24 mW, the threshold current (I_{th}) was 9.64 ± 1.12 mA, the threshold voltage (V_{th}) was 2.05 ± 0.20 V, the differential resistance was 44 ± 17 Ω at I_{th}, and the emission wavelength was 859.6 ± 3.3 nm at $1.2 \times I_{th}$. The polarization directions of VCSELs in a 8×8 array were within 30° along $[\bar{2}33]$ (0°). The selectivity of polarization is sufficient up to the total output power of 4 mW. At 20 mA, the power ratio of 0° to 90° was 15.0 dB where the total power was 3.9 mW.

Compared with the conventional (100) VCSELs we fabricated, the (311)B ones are not significantly different; the maximum powers exceed 1 mW and the threshold current densities (J_{th}) are $1-4$ kA/cm^2. The slightly higher J_{th}(3.1 kA/cm^2), compared with (100), is considered to be due to the lower reflectivity of the top-DBR and the longer cavity length (the emission wavelength at I_{th} was longer than the designed optical cavity length of 850 nm). It is noted that the threshold voltage is equivalent to that on (100) (2.6 V at I_{th} of 4.7 mA has been reported by our group in VCSELs on

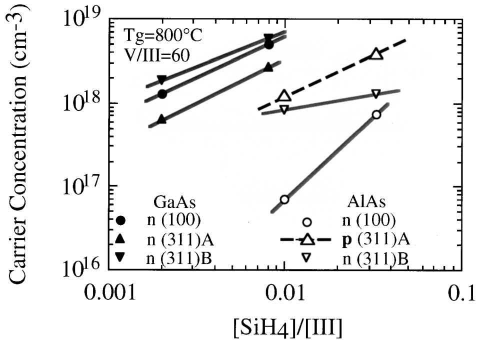

FIG. 3. Carrier concentration of GaAs and AlAs on (311)B, (100), and (311)A as a function of the mole fraction of SiH_4 to the group III sources.

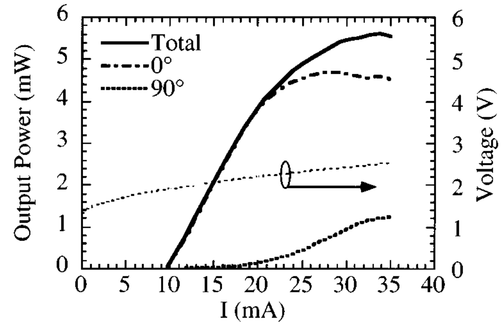

FIG. 5. Output power and voltage as a function of current in cw mode at RT, where the $[\bar{2}33]$ direction is defined as 0°.

(100)).[7] This indicates that the resistance of p-DBR on (311)B is as low as that on (100). From the above results, the performances of VCSELs on (311)B are confirmed to be on the same level as those on (100).

In summary, the MOCVD growth conditions for VCSELs on GaAs (311)B substrates have been examined, and the proper growth conditions for C-doped DBRs have been found. The 0.85 μm 8×8 VCSEL array showed good device characteristics—low threshold voltage of 2.1 V and high maximum power of 4.1 mW, quite similar to the characteristics of VCSELs grown on (100). The polarization directions of each element in the 8×8 array were stable and in an orderly direction along [233].

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