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650nm-Band High Power AlGaInP Visible Laser Diodes Fabricated by Reactive Ion Beam Etching Using Cl_2/N_2 Mixture

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650nm-band AlGaInP visible laser diodes having stable fundamental-transverse-mode at high temperature were demonstrated by using electron cyclotron resonance reactive ion beam etching (ECR-RIBE). Epilayers were etched using a Cl_2/N_2 mixture, resulting in symmetric mesa stripe and very smooth surface. 700μm-long and 6%/80% coated devices were fabricated, resulting in the threshold current of 46mA at room temperature. Single-mode operation over 30mW is obtained up to 60°C.

1. INTRODUCTION

AlGaInP visible laser diodes are of great interst for applications such as optical data storage due to their shorter wavelength [1-3]. Misoriented substrates are used for laser fabrication in order to suppress the spontaneous ordering of crystals [4-5], to increase p-type doping level in the cladding layer [6], and to obtain abrupt interface within one monolayer [7]. However, the mesa stripe becomes asymmetric when the laser mesa is etched by using ordinary wet etching process. As a result, the transverse-mode becomes unstable especially at higher temperature. A dry etching process is much desirable for laser fabrication because of its anisotropic etching. But AlGaInP crystal contains four different elements and this make the dry etched surface rough, which is due to the different volatility of the elements and their reactive products. Especially, the difference in volatility of $InCl_x$ and PCl_x make Cl-based dry etching difficult in Indium- and Phosphorus- containing III-V compounds [8-9]. We realized smooth and symmetric mesa with electron cyclotron resonance reactive ion beam etching (ECR-RIBE) by using Cl_2/N_2 mixture. We report on 650nm-band high power AlGaInP visible laser diodes with stable fundamental-transverse-mode up to 60°C.

2. EXPERIMENTAL

For dry etching, a conventional ECR-RIBE was used. The etching chamber was evacuated to below 1×10^{-6} Torr before etching and Cl_2 and N_2 gas was then injected to plasma chamber. The working pressure was 1×10^{-3} Torr and the gas flow ratio Cl_2/N_2 was 3.5. The Cl_2/N_2 ion beam was extracted and accelerated to 500eV. The dry etching was done at room temperature. The etching mask was 400nm-thick SiO_2 made by plasma chemical vapor deposition and the mask was patterned by CF_4 reactive ion etching using a photoresist mask. To test the Cl_2/N_2 dry etiching process, we used metalorganic vapor phase epitaxy (MOVPE) grown samples of $Ga_{0.5}In_{0.5}P$ and $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ with a 15nm-thick GaAs cap layer. The etch rate was about 50nm/min for both $Ga_{0.5}In_{0.5}P$ and $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$, and the selectivity between the epilayers and SiO_2 mask was a factor of 5.

The scanning electron microscope (SEM) photograph of etched $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ is shown in Fig. 1. The AlGaInP layer was etched very smoothly and no roughness was observed on the etched surface. The smooth surface can be realized by using Cl_2/N_2 mixture, which contributes to the reduction of the Cl radical density in the processing plasma [9].

Figure 2 shows the frontal cross sectional view of the transverse-mode stabilized laser structure. The epitaxial growth of the laser structure was carried out by three-step low-pressure MOVPE in a horizontal reactor. The misoriented (100) n-GaAs substrate ($n=2\times10^{18}cm^{-3}$) toward [011] direction was used in order to make oscillation wavelength shorter, to obtain an abrupt interface, and to

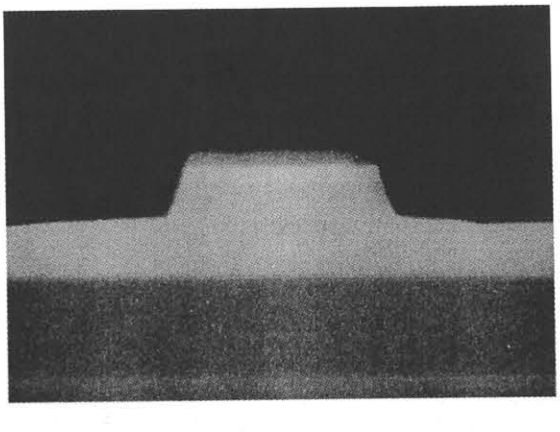

Fig. 1. Scanning electron microscope photograph of etched laser mesa.

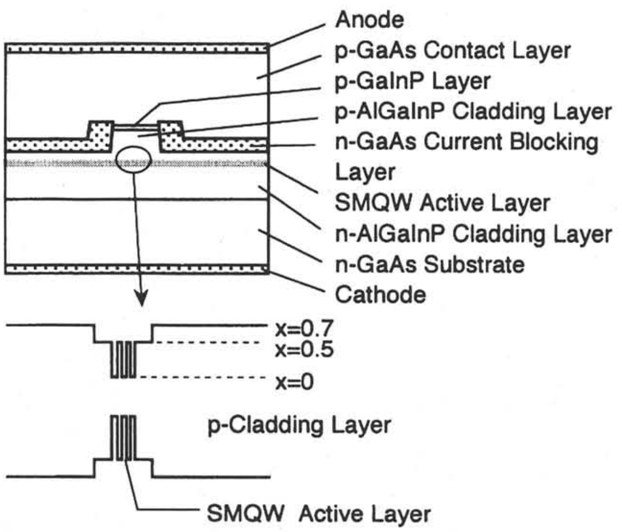

Fig. 2. Schematic cross section and band diagram of the laser.

increase p-type doping level [7]. The growth temperature was 760°C. The double heterostructure consists of the following layers: an n-GaAs buffer layer ($0.3\mu m$, $n=1\times10^{18}cm^{-3}$), an n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layer ($1.3\mu m$, $n=5\times10^{17}cm^{-3}$), an undoped strained multiple quantum well (SMQW) active layer, a first p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layer ($p=4\times10^{17}cm^{-3}$), a p-$Ga_{0.5}In_{0.5}P$ etch stop layer, a second p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layer ($1.1\mu m$, $p=5\times10^{17}cm^{-3}$), a p-$Ga_{0.5}In_{0.5}P$ layer ($p=1\times10^{18}cm^{-3}$), and a p-GaAs cap layer ($p=5\times10^{18}cm^{-3}$). The band diagram of the SMQW active layer is also shown in Fig. 2. Al composition is denoted by x. The SMQW active layer consists of three $Ga_{0.44}In_{0.56}P$ wells separated by $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barriers.

The laser mesa was made by dry etching process described above. Before regrowth of an n-GaAs current blocking layer, the laser wafer was slightly etched using sulfuric acid. Finally, a p-GaAs contact layer ($p=5\times10^{18}cm^{-3}$) was overgrown. The width of the ridge stripe was $5.1\mu m$ and the cavity length of the lasers was $700\mu m$.

3. RESULTS

Figure 3 shows temperature dependence of output power versus current characteristics of antireflection (6%)/high reflection (80%) coated laser. Single-mode operation over 30mW is obtained up to 60°C as shown in Fig. 3. The typical threshold current of this device was 46mA at 20°C. The lasing wavelength was 657nm at 20°C under 30mW output power.

The beam divergence angles parallel and perpendicular to the junction plane were 8.2° and 20.9°, respectively, resulting in an aspect ratio of 2.55. The total internal loss, which can be estimated from the differential

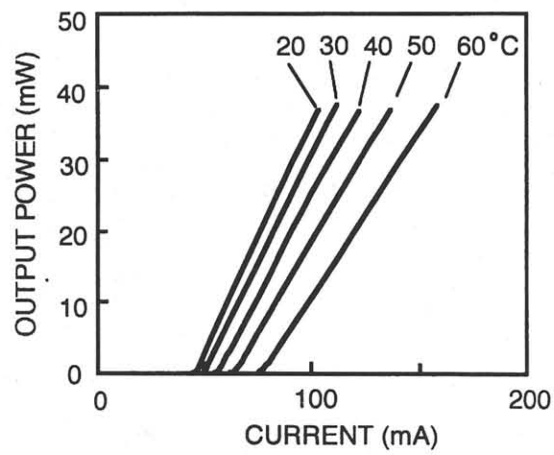

Fig. 3. Temperature dependence of output power vs current characteristics of 6%/80% coated laser.

quantum-efficiency dependence on cavity length, was about $15cm^{-1}$. This value is close to that of lasers fabricated by conventional wet etching process and there seems to be no influence such as etching damage during dry etching process.

Figure 4 shows the comparison of the far field pattern in the direction parallel to the layers between the test sample (a) , which made by using Cl_2/N_2 ECR-RIBE, and the control sample (b), which by ordinary wet etching

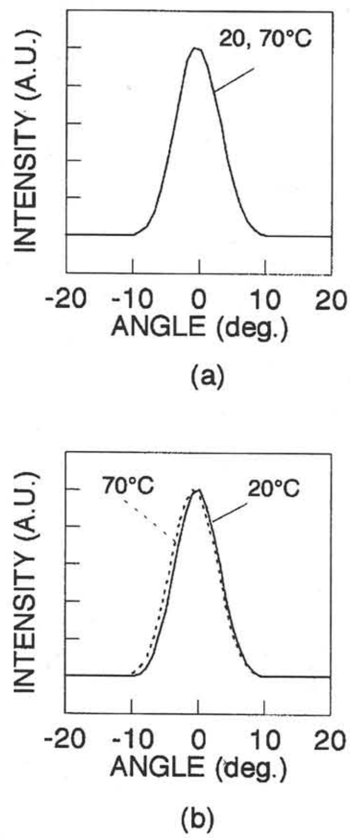

Fig. 4. Far field pattern in the direction parallel to the layers of (a) the test sample and (b) the control sample.

process using sulfuric acid. The measured temperatures were 20°C and 70°C and the output power was 5mW. No change was observed for the test sample (Fig. 4 (a)). In the case of the control sample (Fig. 4 (b)), the far field pattern moved at 70°C, indicating unstability of transverse-mode.

Figure 5 shows life test results at 60°C under the output power of 25mW. The lasers have been operating for over 1000h, and the degradation rate was as low as lasers fabricated by the ordinary wet etching process.

4. CONCLUSIONS

650nm-band high power AlGaInP visible laser diodes were fabricated by ECR-RIBE. Epilayers were etched using Cl_2/N_2 mixture, resulting in symmetric mesa stripe and very smooth surface. 700μm-long and 6%/80% coated devices were fabricated, resulting in the threshold current of 46mA at 20°C and single-mode operation over 30mW is obtained up to 60°C. The dry etching process with Cl_2/N_2 mixture is suitable for fabrication of AlGaInP lasers having stable fundamental-transverse-mode. Further optimization, active layer structure *et al.*, will make high reliability and these lasers are promising candidate for practical application to high optical data storage.

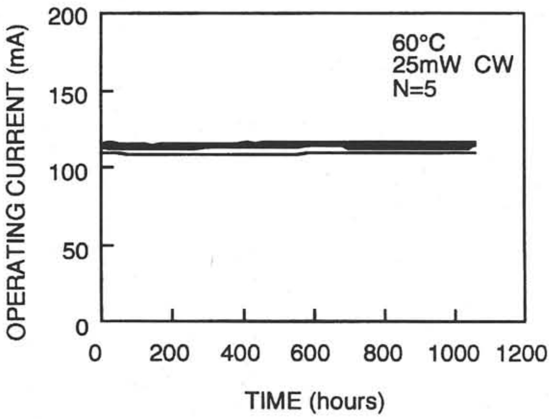

Fig. 5. Life test results at 60°C under a constant output power of 25mW.

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