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632.7 nm CW Operation (20°C) of AlGaInP Visible Laser Diodes Fabricated on (001) 6° off toward [110] GaAs Substrate

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632.7 nm continuous wave operation was achieved at 20°C, by an AlGaInP visible laser diode (LD) with an AlGaInP quaternary active layer fabricated on a (001) GaAs substrate with a misorientation angle of 6° toward the [110] direction. The epitaxial layers for the laser structure are grown by metalorganic vapor phase epitaxy. The lasing wavelength is almost the same as that for He–Ne lasers. Lasing wavelengths for the LDs were also compared with wavelengths for those fabricated on an exact (001) orientation substrate.

KEYWORDS: visible laser diode, AlGaInP, off-angle-substrate, continuous wave operation, natural superlattice, MOVPE

Short wavelength laser diodes (LDs) are very attractive light sources for many applications, including high density optical disk memory systems, bar-code readers, and laser printers. In recent years, several efforts have been made to realize continuous-wave (cw) operation at a wavelength shorter than 640 nm in the AlGaInP alloy system. To shorten the lasing wavelength for AlGaInP visible LDs to such a wavelength range, two approaches have been employed. One is using an AlGaInP quaternary active layer,[1,2] and the other is using a multiquantum-well (MQW) active layer.[3,4] In either case, it is important to control the natural superlattice (NSL) formation[5] in the materials for active and cladding layers, because the energy gaps for AlGaInP crystals, grown by metalorganic vaper phase epitaxy (MOVPE), decrease with increasing degree of NSL formation in them. Also, the energy difference is up to about 80 meV, even for the same composition (x) of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ alloys.[5,6] The difference corresponds to over 20 nm in lasing wavelengths.

Concerning the NSL formation control, it has been clarified that the surface orientation of GaAs substrates quite strongly influences the NSL formation.[7–9] AlGaInP layers on (111)B and (011) GaAs substrates show no NSL and the highest energy gap of 1.918 eV.[7] Although (001) substrates with small off angles toward [$\bar{1}$10] exhibit some decrease in energy gap, those with off angle toward [110] show some increase.[9,10] Thus, off-angle-substrates toward [110] have a large advantage in regard to shortening the lasing wavelength; AlGaInP alloys with lower Al composition can be used for the active layer, keeping the lasing wavelength as short as that for higher Al composition alloys. Off-angle-substrates have already been applied for the GaInP active layer laser diodes.[10–12] However, as far as we know, there has been no report for AlGaInP quaternary active layer laser diodes. This letter reports 630 nm band AlGaInP visible LDs with a quaternary active layer fabricated on a (001) 6° off toward [110] GaAs substrate. At 20°C, 632.7 nm cw operation was achieved. Comparison was also made for LDs grown on exact (001) substrates and on off-angle-substrates.

Figure 1 shows a diagrammatic view of the laser structure. The epitaxial layers were grown by three step low-pressure (70 Torr) MOVPE. The source materials are trimethylindium (TMIn), triethylgallium (TEGa), trimethylaluminum (TMAl) and PH_3 for AlGaInP quaternary layers. Trimethylgallium (TMGa) and AsH_3 were used for GaAs layers. The doping sources are dimethylzinc (DMZn) and Si_2H_6 for p-type and n-type layers, respectively. Growth temperature was 660°C. The double heterostructure (DH), grown on (001) 6° off toward [110] substrates, consists of: (1) n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ outer cladding layer ($d=0.7$ μm), (2) n-$(Al_{0.6}Ga_{0.4})_{0.5}In_{0.5}P$ inner cladding layer ($d=0.25$ μm), (3) undoped-$(Al_{0.19}Ga_{0.81})_{0.5}In_{0.5}P$ active layer ($d=96$ nm), (4) p-$(Al_{0.6}Ga_{0.4})_{0.5}In_{0.5}P$ inner cladding layer ($d=0.25$ μm), (5) p-$(Al_{0.19}Ga_{0.81})_{0.5}In_{0.5}P$ etching stopping layer ($d=5$ nm), (6) p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ outer cladding layer ($d=0.7$ μm), (7) p-$Ga_{0.5}In_{0.5}P$ layer ($d=10$ nm), and (8)

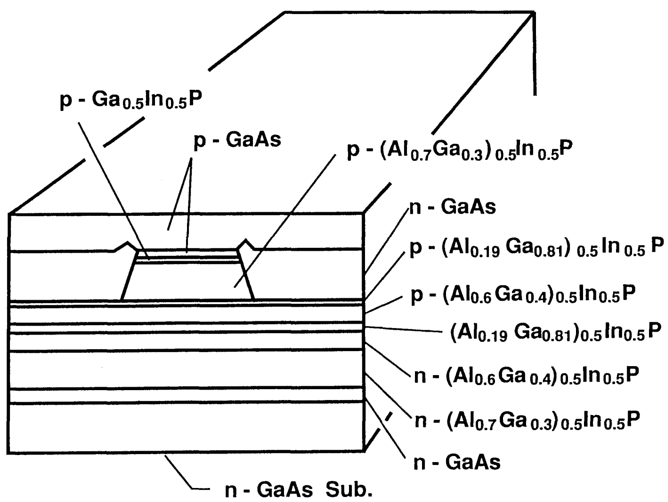

Fig. 1. Diagrammatic view of the laser structure with an AlGaInP quaternery active layer. A transverse mode stabilized ridge shaped laser structure was employed.

p-GaAs cap layer. The mesa shaped outer cladding layer was buried with n-GaAs layers. The surface was covered with a p-GaAs contact layer. The stripe width is about 5 μm at the mesa bottom.

Figure 2 shows light output versus injection current characteristics for cw operation. The inset shows the lasing spectrum under 20°C, 2 mW condition. The LD was mounted on a diamond heat sink. The cavity length was 345 μm. The threshold current at 20°C was 92 mA. The lasing wavelength was 632.7 nm at 20°C, 2 mW. This wavelength is almost the same as that for He–Ne lasers (632.8 nm). The full width at half-maximum values for beam divergence angles were determined to be 35° and 7.8°, vertical and parallel to the junction plane, respectively, by far-field measurements.

Figure 3 shows the temperature dependence of threshold current under the pulsed condition. Characteristic temperature To values for 20–40°C and for 60–80°C were 60 K and 40 K, respectively. The values are less than those for GaInP active layer laser diodes, whose To value is typically over 100 K. This threshold current

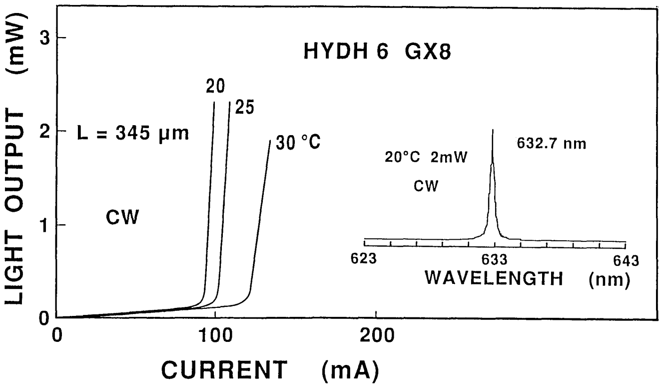

Fig. 2. Light output versus injection current characteristics of an LD for cw operation. The inset shows a lasing spectrum under 20°C, 2 mW conditions.

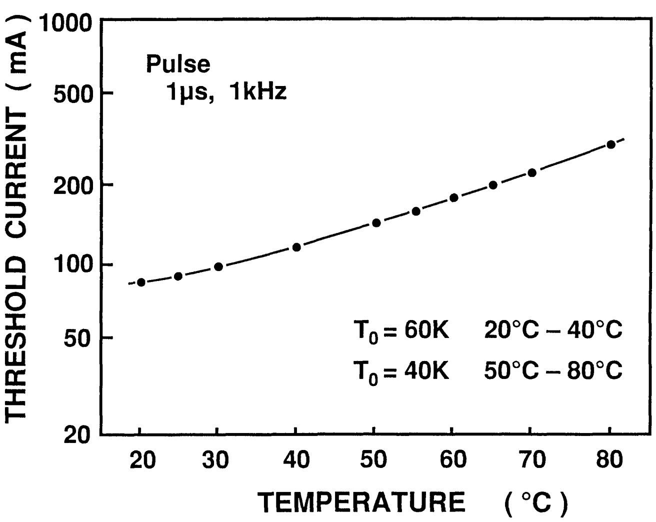

Fig. 3. Temperature dependence of the threshold current under a pulsed condition. The pulse repetition rate was 1 kHz and the pulse width was 1 μs.

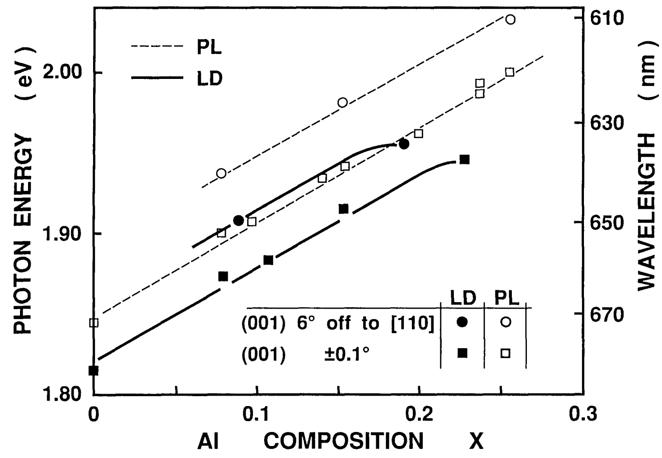

Fig. 4. Lasing photon energy and lasing wavelength (25°C) versus the active layer Al composition, for (001) 6° toward [110] substrates and exact (001) orientation substrates. Cladding layer Al compositions and thicknesses were fixed, as shown in Fig. 1.

dependence can be explained by carrier leakage from the active layer to the cladding layers in the conduction band.

Figure 4 shows lasing photon energy (lasing wavelength) versus the active layer Al composition. The data for LDs grown on substrates with the exact (001) orientation were also plotted for comparison. The LDs' cladding layer Al composition and thickness were fixed, as shown in Fig. 1. The solid line indicates lasing photon energy under cw operation. 632.7 nm at 20°C and 634.2 nm at 25°C were obtained as the shortest wavelengths, in the present experiments, for a (001) 6° off toward [110] substrate, while 637.3 nm at 25°C was obtained for an exact (001) substrate. The broken line indicates photoluminescence (PL) peak energy from thick (1.2 μm) epitaxial layers. The shortest wavelengths, at which cw operation could be obtained, were limited by an active layer temperature increase, accelerated by the relatively high threshold current density and the small characterictic temperature To, due to decreased barrier height between the active and cladding layers. The active layer temperature increase was suggested by the data, wherein the difference between lasing photon energy and PL peak energy becomes larger as the active layer Al composition increases.

The 6° off-angle-substrates allowed lower Al composition by $\Delta x = 0.06$ in the quaternary active layer to obtain the same lasing wavelength. For lower Al composition, AlGaInP alloys tended to show a better crystalline quality. Substrate with off angles toward [110], on which higher energy gap materials grow, was demonstrated to be preferable for shortening the lasing wavelength especially for quaternary AlGaInP active layer LDs.

In conclusion, we have achieved 632.7 nm cw operation at 20°C for an LD fabricated on a (001) 6° off toward [110] substrate. The advantage is shown for off-angle-substrates, by making a comparison between LDs with (001) exact substrates and those with off-angle-substrates.

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