Extended Abstracts of the 1991 International Conference on Solid State Devices and Materials, Yokohama, 1991, pp. 390-392

Invited

Visible Semiconductor Lasers—toward Shorter Wavelength

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This paper reviews characteristics of visible semiconductor lasers with AlGaInP multiquantum well active layers. Shortening of the wavelength by more than 35 nm under continuous wave operation is experimentally achieved at room temperature. Discussion about the limitation of further wavelength shortening is also shown.

I. Introduction

Semiconductor lasers emitting at short wavelengths are very useful for improvements in applications such as concentration of the recording density of the optical discs, enhancement of the sensitivity of optical receivers, and realization of medical applications using photochemical reaction, etc.

Therefore, lasers using wide bandgap semiconductor materials [1, 2] or using second harmonic generation [3] have been widely studied. Among them, the AlGaInP laser is one of the most reliable devices [4, 5]. By using a GaInP bulk active layer, the emitting wavelength of the semiconductor lasers has been shortened by 100 nm, compared with conventional 780 nm AlGaAs lasers.

There is an ongoing effort to achieve much shorter wavelengths from AlGaInP lasers. There are three main methods to make the bandgap wider. One is to make the bulk active layer contain aluminum [6]. Another is to disorder the naturally induced superlattice structure by using misoriented substrates [7]. Combination of these two methods has also been achieved [8]. The third method is to adopt a multiquantum well (MQW) structure in the active layer [9, 10]. The MQW structure can improve the device characteristics such as threshold current, quantum efficiency, etc. [11] so that this structure is thought to be most promising for practical shorter wavelength lasers.

In this paper, we review experimental results on wavelength shortening as well as the device characteristics of GaInP / AlGaInP MQW lasers. Then, the limitation of further wavelength shortening are briefly discussed.

II. GaInP MQW lasers

Figure 1 shows a schematic structure of the transverse-mode stabilized GaInP MQW laser [11]. This structure is grown on <001> oriented GaAs substrate by using three-step metalorganic vapor phase epitaxy. The ridge is 5 μm wide at the bottom. The active layer consists of five GaInP well layers with 10 nm thickness and six $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barrier layers with 4 nm thickness. The cladding layers consist of 1 μm thick $(Al_{0.6}Ga_{0.4})_{0.5}In_{0.5}P$. The thickness of the p-cladding layer adjacent to the ridge is 250 nm. The cavity length is 350 μm. After cleavage, sulfur facet treatment is done to increase the catastrophic optical damage level [12]. The reflectivity of the front and rear facets are 6 % and 76 %, respectively.

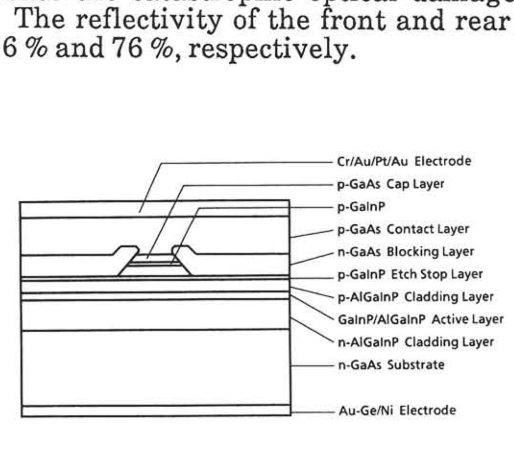

Fig. 1 Schematic structure of GaInP MQW laser.

Curve (a) in Fig. 2 is the light output versus current characteristic of GaInP MQW laser under continuous wave (CW) operation at room temperature (RT). The threshold current and differential quantum efficiency are 35 mA and 61 %, respectively. The kink level, the maximum light output below which the output linearity is kept, is 48 mW. The emitting wavelength and its temperature dependence are 677nm and 0.2 nm / deg., respectively. The characteristic temperature is 120 K around room temperature. The curve (b) in Fig. 2 is the same characteristic of the laser with GaInP bulk active layer. The other structural parameters including the facet reflectivity are the same as those of the MQW laser. The threshold current and differential quantum efficiency are 54 mA and 40 %, respectively. The kink level is only 20 mW. The emitting wavelength and its temperature dependence are 681 nm and 0.3 nm / deg., respectively. The characteristic temperature is about 100 K around room temperature.

From above results, it is obvious that the GaInP MQW achieves many improvements; such as wavelength shortening by 4 nm, suppression of temperature dependence of emitting wavelength by 30 %, a reduction of threshold current by 35 %, an increase of differential quantum efficiency by 50 %, an increase of kink level by 140 %, and an increase of the characteristic temperature by 20 %. Moreover, as shown in Fig. 3, stable single transverse mode operation is observed even under high optical output.

III. AlGaInP MQW lasers

We have succeeded RT CW operation of AlGaInP MQW lasers [11]. The active layer consists of five 10 nm thick $(Al_{0.15}Ga_{0.85})_{0.5}In_{0.5}P$ well layers and six $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barrier layers. The cladding layers consist of 4 nm thick $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$. A <001> oriented GaAs substrate is used. The other structural parameters except facet reflectivity are as same as those of the GaInP MQW laser.

Figure 4 shows the spectrum of an AlGaInP MQW laser without facet coatings under RT CW operation at 2mW. The emitting wavelength is 643.5 nm, which is shorter by more than 35 nm than that of the lasers with a GaInP bulk active layer. The color is bright red. The threshold current, differential quantum efficiency, and kink level are 76mA, 21 %, and 9.5 mW, respectively.

IV. Discussion on limitation of further wavelength shortening

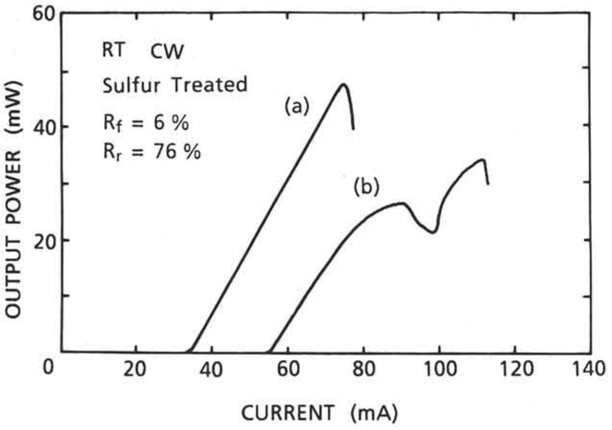

Fig. 2 Light output versus current characteristics. (a) : GaInP MQW laser, (b) : laser with GaInP bulk active layer.

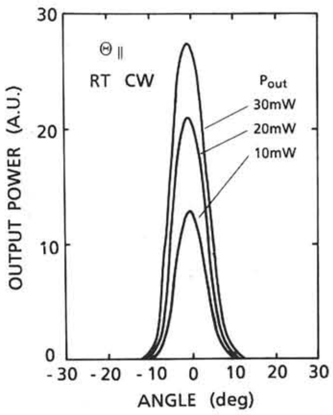

Fig. 3 Far field patterns of GaInP MQW laser.

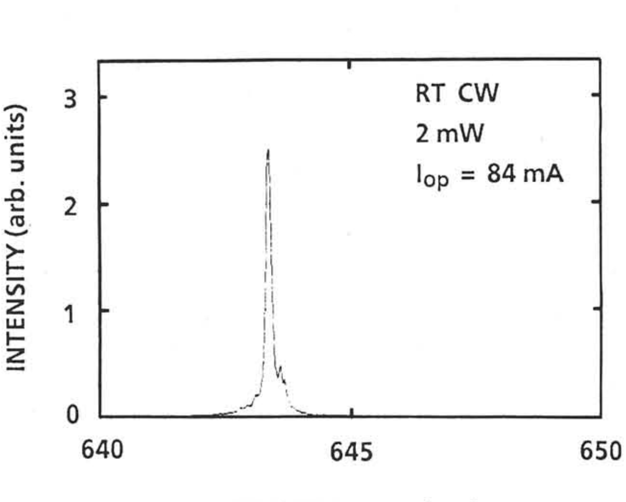

Fig. 4 Emission spectrum of AlGaInP MQW laser

The emitting wavelength of MQW lasers can be shortened by both reducing the well thickness and increasing aluminum content of the well. In this chapter, limitations of these approaches are discussed.

The solid line in Fig. 5 shows relation between peak wavelength of photoluminescence (PL wavelength) and aluminum content of a 5 nm thick well layer. The dashed line shows relation between PL wavelength and AlGaInP bulk crystal. These layered structures are grown on a <001> oriented GaAs substrate.

The PL wavelength of the MQW is shorter by more than 20 nm than that of the bulk crystal at every aluminum content. If the minimum conduction band discontinuity for getting laser operation is assumed to be 0.15 eV, the maximum aluminum content in the quantum well is limited to 0.2 based on an AlGaInP band diagram [13]. The PL wavelength of the MQW at this aluminum content is 605 nm. Since the emitting wavelength is generally longer by 10 nm than the PL wavelength, lasers emitting around 615nm may potentially be fabricated.

Furthermore, if a disordering effect is added, emitting wavelength can be shortened by about 20 nm [7]. In this case, orange emission around 600 nm wavelength would be possible. However, since there are many unknown factors about crystal quality, threshold current, maximum light output, reliability, etc, the realization of orange lasers still depends on further effort in the future.

Very recently, several papers reported theoretical and experimental results on using

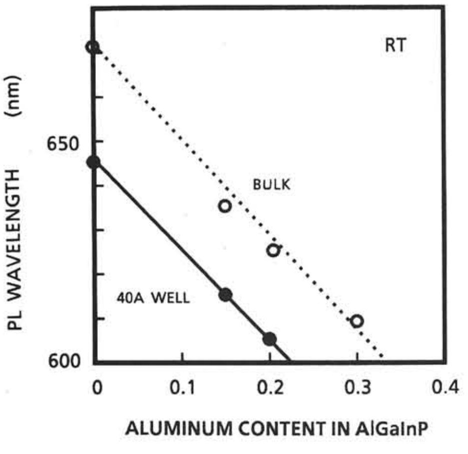

Fig. 5 Relation between peak wavelength of photoluminescence and aluminum content. Solid line : MQW structure, dashed line : bulk crystal.

multiquantum barriers (MQB) locating in the cladding layer, which can reflect carriers back into the active layer [14]. They predicted an increase of the effective conduction band discontinuity by up to about 0.2eV. Therefore, if a MQB laser is realized, yellow laser might be possible.

V. Conclusions

Wavelength shortening of AlGaInP lasers by adopting MQW structure was described. The other device characteristics were also improved by this structure. Further effort might achieve orange and yellow CW operation at RT in the future.

Acknowledgments

The authors would like to acknowledge Mr. T. Onuma and Dr. M. Ogura for their continued encouragement. They also wish to thank Miss. C. Utoh for her helpful support.

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