Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 710-712 **PC-9-7**

Operating Current Dependence of CdZnSe/ZnMgSSe Laser Diodes on Band Gap and Carrier Concentration of P-Type Cladding Layer.

Shin'ichi Nakatsuka, Jun Gotoh, Kazuhiro Mochizuki, Akira Taike, Masahiko Kawata, and Masayuki Momose

Central Research Lab. Hitachi Ltd.
Higashi-koigakubo 1-280, Kokubunji, Tokyo 185, Japan

The dependence of CdZnSe/ZnMgSSe laser diode characteristics on the band gap and carrier density of the cladding layer is investigated theoretically to provide quantitative guidelines for cladding layer design. The carrier overflow from the active layer to the cladding layer and the recombination current at the active layer are calculated taking band bending around the active layer into consideration. The calculated results are consistent with experimental and reported characteristics.

1. INTRODUCTION

ZnMgSSe is one of the most promising materials for blue-green laser diodes since it has an exceptionally wide band gap for a II-VI semiconductors that lattice-matched to a GaAs substrate. This feature makes it possible to fabricate a heterostructure with a large band offset and excellent crystalline quality. Continuous operation at room temperature has be achieved in lasers using this material[1)2)].

However, a tradeoff exists between achieving a large band-gap and a high doping concentration[3)] in ZnMgSSe because of Fermi level pinning caused by ampoteric defect formation[3)] or localized centers[4)]. The MgS content of $Zn_{1-x}Mg_xS_ySe_{1-y}$ is usually chosen to obtain a carrier concentration of more than $10^{17}cm^{-3}$. However, there are no quantitative guideline for determining the concentration of a ZnMgSSe cladding layer.

In this paper, we analytically investigate the dependence of laser characteristics, such as threshold current density and operating voltage, on the carrier concentration and band-gap of a ZnMgSSe cladding layer for CdZnSe/ZnMgSSe laser diodes. The recombination current at the active layer and the overflow current to the cladding layer is calculated for various carrier concentrations and band-gaps of the cladding layer. The influence of the carrier concentration on the laser diode characteristics is estimated taking band bending around the active layer and carrier overflow enhancement by the electric field in the cladding layer into consideration.

2. ANALYZED MODEL

First, we calculated the optical gain, quasi-Fermi level, and recombination current in a 10-nm ZnCdSe single quantum well active layer. The relationship between the optical gain and the quasi-Fermi level can be calculated by using the effective mass theory and density of state formalism.[5)] The relationship between the recombination current and the quasi-Fermi level can also be calculated with a similar technique. The quasi-Fermi level necessary for laser operation is determined using the parameters shown in Table 1.

Band bending in the cladding layer is assumed to keep the quasi-Fermi level of the active layer and the Fermi level of the cladding layer equal as shown in Fig. 1. We examined upward and downward band bending, which correspond to low and high carrier concentrations in the p-cladding layer. When the carrier concentration of the p-type cladding layer is sufficiently high, depletion regions are formed at both sides of the active layer. The amount of space charge in the depletion region is expressed as follows

$$Q = \sqrt{\frac{2\varepsilon_0 \varepsilon_s V_f}{q} N_a}$$

When the carrier density of a p-type cladding layer is too low to supply sufficient holes to the active layer even if the energy band of this layer is flat, we assumed upward band bending as shown in Fig. 1(b). In this case the space charge of the carrier accumulated region can be expressed by the following form by solving Poisson's equation using

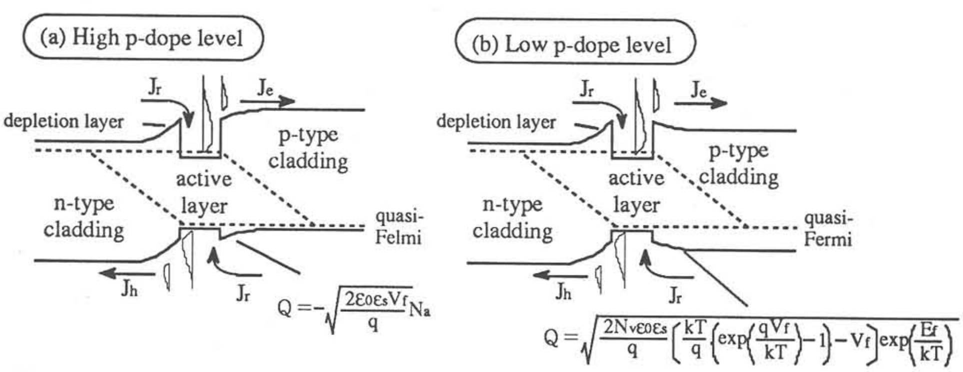

Fig. 1 Calculated band model of the laser diodes. Band bending takes place to match the quasi-Fermi level of the active layer to the Fermi level of the cladding layer. In the p-type cladding layer, a depletion layer is formed when the doping level is high, while a carrier accumulated layer is formed when the doping level is low.

Table 1

effective mass	electron	0.16 mo
	heavy hole	0.78 mo
	light hole	0.15 mo
mobility	electron	100 cm^2/V·s
	hole	10 cm^2/V·s
diffusion length	electron	0.5 μ m
	hole	0.1 μ m
laser diode parameter	cavity length	1 mm
	cavity loss	20 cm^{-1}
	mirror reflectivity	25%

the effective density of state assumption for the valence band

$$Q=\sqrt{\frac{2N_v\varepsilon_0\varepsilon_s}{q}\left[\frac{kT}{q}\left\{\exp\left(\frac{qV_f}{kT}\right)-1\right\}-V_f\right]\exp\left(\frac{E_f}{kT}\right)}$$

Then, we modified the carrier balance in the active layer to keep pThe leakage current could be determined based on the diffusion of minority carrier over the heterobarrier[6]. We estimated the diffusion constant and diffusion length from the electron and hole mobility of the ZnMgSSe by assuming a carrier lifetime of 1 nsec. When the carrier density of the cladding layer is low, the resistivity increases and an electric field is formed in the cladding layer. This electric field affects the leakage of the minority carriers. The effective diffusion length, taking the effect of the electric field into account, is obtained as follows

$$L_{eff}=\frac{1}{\sqrt{\left(\frac{1}{L}\right)^2+\left(\frac{qE}{2kT}\right)^2}}+\frac{qE}{2kT}$$

3. RESULTS AND DISCUSSION

First, we investigated the threshold current of the laser diodes. Figure 2 shows the relationship between the carrier density and E_g for various calculated threshold current densities of a laser diode at a lasing wavelength of 520 nm. A carrier density increase from 10^{16} to 10^{17} cm^{-3} has almost the same effect on J_{th} as an E_g increase of 0.07 eV would have. Figure 2 also shows the actual threshold current density of two laser diodes with a similar structure fabricated in our laboratory. The difference in the carrier density in their p-cladding layer is mainly due to the difference in their growth temperatures. The experimental values for Jth are consistent with the calculated results but a little larger than expected. This difference is mainly attributable to current spreading in the gain-guiding laser diode.

Figure 3 shows the calculated threshold current density versus the E_g of the p-cladding layers. The maximum carrier density that can be obtained for a given Eg is shown as a dashed line in Fig. 2 and is thought to be the present limiting factor on nitrogen doping in a monolayer

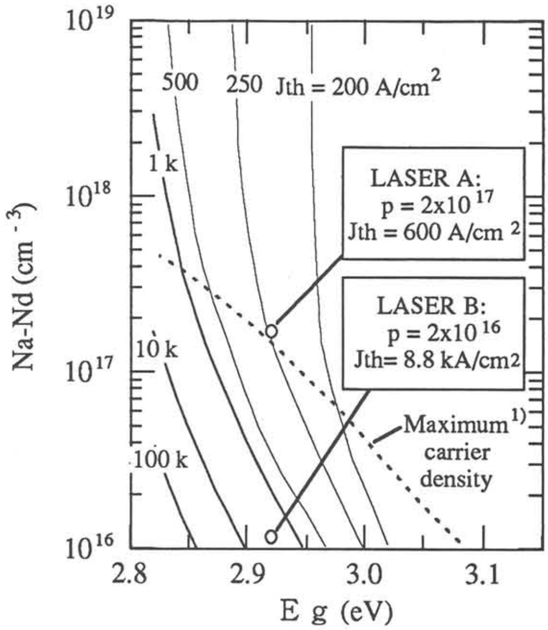

Fig. 2 Na-Nd versus Eg of a ZnMgSSe cladding layer of a 520-nm laser diode for various calculated threshold current densities.

ZnMgSSe lattice matched to a GaAs substrate. The calculated values of J_{th} are consistent with the reported minimum J_{th} for each wavelength range[1)7)8)].

Our calculated results imply that for a laser diode with a wavelength of less than 500 nm, the ZnMgSSe composition that provides a threshold current density of less than 1 kA/cm^{-2} lies in a region where the E_g is greater than 2.95 eV and a carrier density of less than 10^{17} cm^{-3} can be obtained. On the other hand, in the case of a laser diode

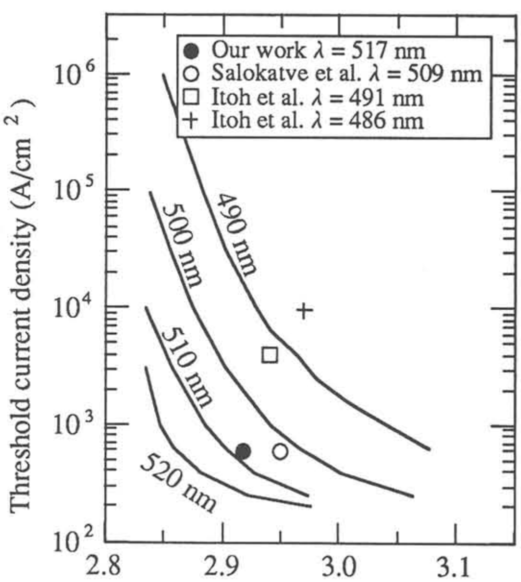

Fig. 3 Calculated threshold current density versus Eg for various wavelengths with optimum cladding-layer doping levels

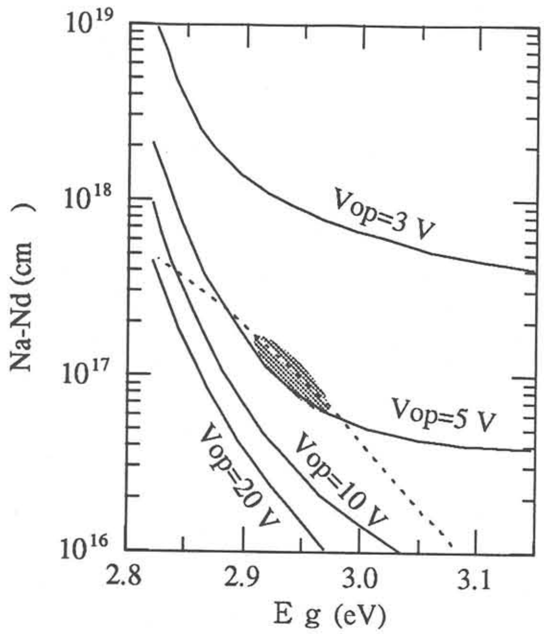

Fig. 4 Na-Nd versus Eg of a ZnMgSSecladding layer of a 520-nmlaser diode for various operating voltages.

with a wavelength of over 520 nm, the optimum Eg is less than 2.9 eV. At this Eg value, a carrier concentration in the p-type cladding layer ranging from 2 to 5 x $10^{17}cm^{-3}$ can be obtained.

The operating voltage of the laser diode is another important factor in II-VI laser diodes because of the low carrier concentration of the p-type cladding layer and the low hole mobility of about 10 $cm^2/Vsec$. Figure 4 shows the carrier density and Eg for various operating voltages of a laser diode with a wavelength of 520 nm. Only the resistance of the 0.5-μm cladding layer is considered as series resistance. The minimum operating voltage that can be obtained in the shaded region of the figure is 5 V.

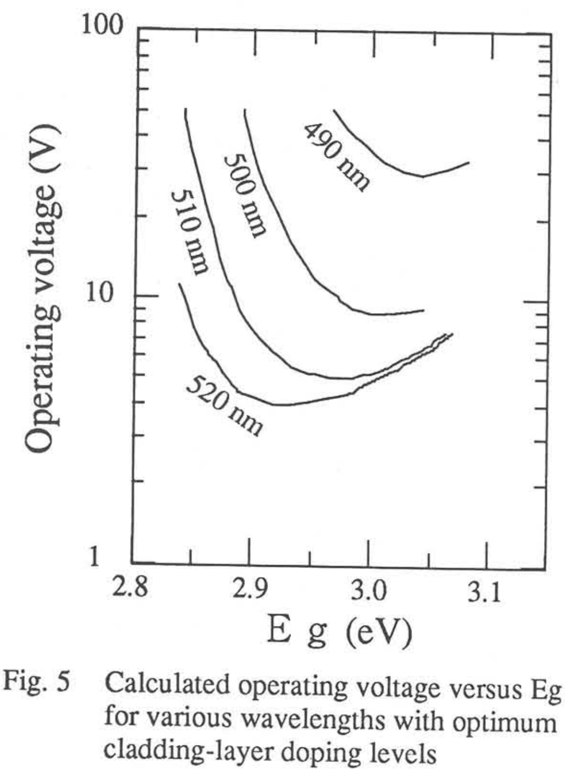

Fig. 5 Calculated operating voltage versus Eg for various wavelengths with optimum cladding-layer doping levels

Figure 5 shows the calculated operating voltage versus the E_g of p-cladding layers with the maximum carrier density that can be obtained for a given lasing wavelength (as in Fig. 3). As shown, the Eg that gives the minimum operating voltage increases as the lasing wavelength decreases. Recent decreases in the battery voltage of electric appliances, though, mean that diode lasers with an operating voltage of less than 5 V are needed. However, our calculated results imply that this can be attained only in laser diodes with a wavelength longer than 520 nm. Therefore, techniques to increase the level of p-type doping to create wide band-gap materials - such as super lattice cladding layers[4)9)] - are needed to develop practical blue laser diodes.

4. CONCLUSION

The dependence of laser diode characteristics on the band gap and carrier density of the cladding layer in ZnMgSSe/ZnCdSe laser diodes was investigated theoretically. The carrier overflow from the active layer to the cladding layer and the recombination current at the active layer were calculated taking into account the band bending around the active layer and the carrier overflow enhancement by the electric field in the cladding layer. The calculated results are consistent with reported results; even in a 520 nm laser diode, the minimum operating voltage is about 5 V. This implies that the techniques to increase p-type doping or the lasing wavelength are needed to achieve a practical blue-green laser diode.

References

(1) N. Nakayama et al. Elec. Lett. **29** (1993) 1488P
(2) A. Salokatve et al. Elec. Lett. **29** (1993) 2192
(3) K. Kondo et al. Appl. Phys. Lett. **64** (1994) 3434
(4) W. Faschinger et al. Appl. Phys. Lett. **66** (1995) 2516
(5) D. Ahn et al. Appl. Phys. Lett. **59** (1991) 2669
(6) I. Suemune Jpn. J. of Appl. Phys. **31** (1992) L95
(7) S. Itoh et al. Jpn. J. of Appl. Phys. **33** (1994) L639
(8) S. Itho et al. Jpn. J. of Appl. Phys. **32** (1993) L1530
(9) A. Ishibashi et al. Proc. of LEOS'94 **PD1.1** (1994)