Optically pumped laser characteristics of blue $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ single quantum well lasers grown on InP

Xuecong Zhou,[a] Martin Muñoz, and Maria C. Tamargo[b]
Department of Chemistry, City College of the City University of New York, New York, New York 10031

Y. C. Chen
Department of Physics and Astronomy, Hunter College of the City University of New York, New York, New York 10021

(Received 22 April 2003; accepted 8 October 2003)

We report the operation of a photopumped blue $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ separate confinement heterostructure single quantum well laser grown lattice matched to InP with a relatively thick quaternary quantum well (~50 Å). Laser emission at 492 nm in the blue was observed. The lasing linewidth is about 5 nm. Based on the temperature dependency of the threshold pumping intensity, the characteristic temperature (T_0) was determined. We also studied a photopumped laser with a similar structure, where the only difference was the quaternary $Zn_xCd_yMg_{1-x-y}Se$ quantum well composition, having laser emission in the green. Comparison of the threshold pumping intensity and T_0 for the blue and green lasers shows a lower threshold pumping intensity and higher T_0 for the green laser. We explain these results on the basis of the difference in carrier confinement between these two structures. An Arrhenius treatment of the temperature dependency of the blue laser threshold pumping intensity gives an activation energy E_a very close to the band gap energy difference between the cladding layer and the quantum well in the conduction band. This points to a carrier loss process through thermalization into the cladding layer. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1630357]

I. INTRODUCTION

Blue semiconductor lasers and light emitting diodes (LEDs) have various potential applications in optoelectronics such as full color displays and high density digital recording. Currently, semiconductor based full color displays are composed of individual LEDs in which the three primary colors (red, green, and blue) are obtained from different materials. This makes semiconductor based full color displays difficult to fabricate. Therefore, it is of interest to fabricate an integrated system in which a single material is grown on a single substrate to cover the full color range. The (Zn,Cd,Mg)Se quaternary alloys can be grown lattice matched to InP substrates with band gap ranging from 2.2 to 3.5 eV.[1] Quantum well (QW) structures entirely lattice matched to InP with a large band gap quaternary $Zn_xCd_yMg_{1-x-y}Se$ alloy as the barrier layers and a ternary $Zn_xCd_{1-x}Se$ as the active layer have been grown with emissions ranging from red to blue,[1,2] covering the entire visible range. Emission from yellow to blue is obtained by simply varying the lattice-matched ZnCdSe quantum well thickness while red emission is achieved by using a strained ZnCdSe active layer with excess Cd. Based on these ZnCdSe/ZnCdMgSe QWs, optically pumped laser structures[3] and LEDs[4] emitting at the spectral range from red to blue have been demonstrated. However, a very thin ZnCdSe well (≤20 Å) must be used in order to achieve blue emission. This results in a broad luminescence emission peak with a full width at half maximum (FWHM) of ~70 meV at 10 K due to well thickness fluctuations. The wavelength of the QW emission is also sensitive to the well thickness. Therefore, it is difficult to obtain reproducible blue emission energies by controlling the well thickness during molecular beam epitaxial (MBE) growth. A $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ QW structure using a quaternary $Zn_xCd_yMg_{1-x-y}Se$ layer instead of a ternary $Zn_xCd_{1-x}Se$ layer as the QW layer has been grown[5] to achieve emission in the blue range with a thicker well, resulting in a narrower emission linewidth, increased reproducibility, and excellent optical characteristics. In this article, we report the operation of photopumped blue lasers made from $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ single quantum well (SQW) laser structures grown on InP with quaternary $Zn_xCd_yMg_{1-x-y}Se$ as the QW material. By varying the QW composition we obtained lasing emission in the green region as well. The properties of these lasers are compared and explained on the basis of the differences in their band structure. The temperature dependency of the threshold pumping intensity can be fitted by a simple Arrhenius relation $I_{th}(T) = C^* \exp(-E_a/kT)$ with an activation energy E_a very close to the band gap energy difference between the cladding layer and the quantum well in the conduction band. This points to a carrier loss process through thermalization into the cladding layer and subsequent diffusion away from the quantum well.

[a] Also at: Department of Physics. email: cong999@yahoo.com
[b] Author to whom correspondence should be addressed; electronic mail: tamar@sci.ccny.cuny.edu

0021-8979/2004/95(1)/7/4/$22.00

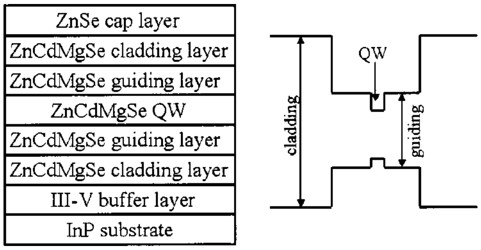

FIG. 1. Schematic of the separate confinement heterostructure laser structure grown and its band gap profile.

II. EXPERIMENTAL DETAILS

The schematic of the separate confinement heterostructure $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ SQW laser structure and its band gap profile are shown in Fig. 1. The samples were grown on (001) epiready InP substrates by MBE in a Riber 2300 system, which includes a III–V growth chamber and a II–VI growth chamber connected by ultrahigh vacuum (UHV) modules. Oxide desorption of the epiready substrate was performed in the III–V chamber by heating to ~490 °C with an As flux impingent on the surface, after which a 160 nm lattice matched InGaAs buffer layer was grown. Then the substrate with the buffer layer was transferred to the II–VI chamber under UHV. Growth of the II–VI material was performed under Se-rich conditions with the growth rate less than 1 μm/h and a VI/II beam equivalent pressure ratio of ~4. Prior to the growth of the laser structure, a Zn irradiation of the InGaAs surface was performed and a 10 nm low temperature $Zn_xCd_{1-x}Se$ interfacial layer was grown at 170 °C in order to improve the crystalline quality.[6] The substrate temperature was then raised to the typical II–VI growth temperature of 270 °C and the laser structure was grown. The SQW blue and green laser structures are nearly the same. They consist of a $Zn_xCd_yMg_{1-x-y}Se$ cladding layer (0.5 μm, $E_g \sim 3.03$ eV), a $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se$ waveguide layer (0.1 μm, $E_g \sim 2.78$ eV), a single $Zn_xCd_yMg_{1-x-y}Se$ QW (50 Å), a top $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se$ waveguide layer (0.1 μm, $E_g \sim 2.78$ eV), a top $Zn_xCd_yMg_{1-x-y}Se$ cladding layer (0.1 μm, $E_g \sim 3.03$ eV), and a ZnSe capping layer (50 Å). This cap layer was used to protect the top cladding layer from oxidation. All the layers except for the ZnSe cap layer were closely lattice matched to the InP substrate. The only difference between the two structures is the QW composition. The optical confinement factor for the fundamental transverse mode calculated with finite element computer analysis is about 1.2%.

The photoluminescence (PL) measurements were made using the 325 nm output of a He–Cd laser as the excitation source and a double spectrometer and photomultiplier tube as a detector.

The samples were thinned to about 100 μm thickness and cleaved into 2-mm-wide bar for photopumping. The experimental setup for photopumping was similar to that described in Ref. 7. A frequency tripled Nd:YAG laser operating at 355 nm wavelength was used as the pumping source. The pulse width and repetition rate of the laser output were 3 ns and 20 Hz, respectively. The pumping beam was focused onto the surface of the wafer to create a stripe geometry excitation region along the (110) direction. A variable attenuator was used to control the pumping intensity. The edge emission of the laser bar was collected by a microscope objective and focused into an optical multichannel analyzer to determine the spectral characteristics.

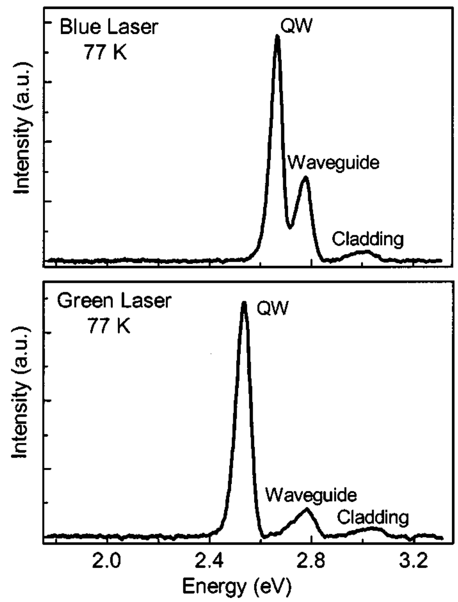

FIG. 2. Photoluminescence spectra at 77 K of the two SQW laser structures.

III. RESULTS AND DISCUSSION

Figure 2 shows the PL spectra at 77 K for our laser structures. Emissions from the cladding layer, waveguide layer, and QW were observed. For the blue laser, the emission peak energies are at 3.03, 2.78, and 2.66 eV, respectively, and FWHM are 96, 57, and 49 meV, respectively; while for the green laser, the emission peak energies are at 3.03, 2.77, and 2.53 eV, respectively, and FWHM are 99, 85, and 57 meV, respectively. No deep level emission was observed. These results indicate very good optical quality of the samples.[8] The (004) double crystal x-ray diffraction (DCXRD) for the blue laser structure is shown in Fig. 3. The FWHM of DCXRD for the cladding and waveguide layers

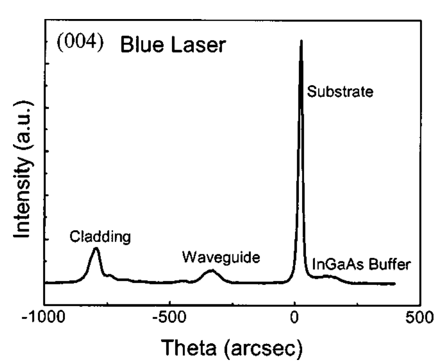

FIG. 3. (004) x-ray rocking curve of the SQW blue laser structure. The FWHM of the cladding and guiding layers are 49 and 70 arcsec, respectively.

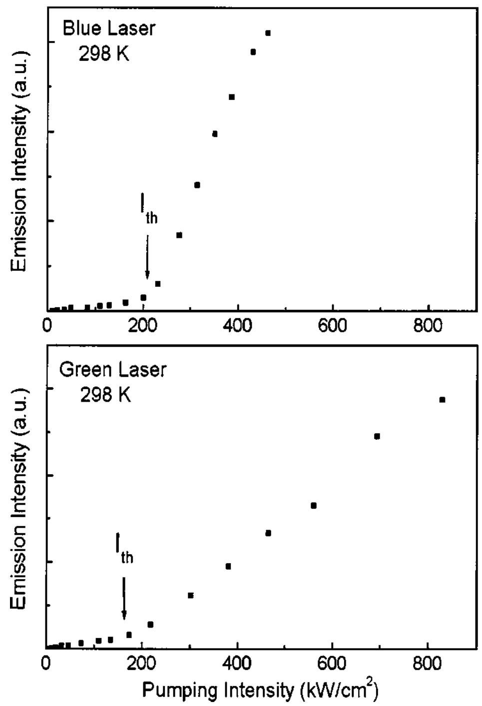

FIG. 4. Output intensity vs pumping intensity at room temperature. The threshold excitation intensity is estimated to be ~220 kW/cm^2 for the blue laser and ~160 kW/cm^2 for the green laser.

are 49 and 70 arcsec, respectively, indicating high crystalline quality of the structure. Similar x-ray results were obtained for the green laser structure.

Figure 4 shows the output intensity from the SQW laser as a function of pumping intensity at room temperature. The pumping-emission plot exhibits a typical superlinear relation below the lasing threshold and a linear relation above the threshold. The threshold occurs at a pumping intensity of 220 kW/cm^2 for the blue laser while it is 160 kW/cm^2 for the green laser. The threshold pumping intensity is influenced by many factors including the laser structure, excitation mode, optical confinement factor, material properties, and crystal quality. Our two lasers have the same layer structure. Both have similar high crystalline and optical quality and the threshold intensity measurements were done under identical conditions. Thus, the higher threshold pumping intensity in the blue laser is attributed to its smaller carrier confinement.

Figure 5 shows the spectra of the blue laser emission at 492 nm as a function of optical excitation intensity at room temperature. A clear linewidth narrowing was observed above the threshold. The lasing linewidth is about 5 nm at 420 kW/cm^2 which is about two times the threshold, and ultimately becomes as narrow as 1.9 nm at several times the threshold. The spectral narrowing near the threshold was not as dramatic as normally expected of lasing spectra when the threshold is crossed. The lack of a dramatic narrowing may be attributed to two factors. First, the linewidth of the spontaneous emission of the quaternary quantum well is already considerably narrower than that of the ternary quantum wells by a factor of two. Second, the quantum well levels of the samples are close to the band gap energy of the barrier layers. The coalescence of the quantum well and barrier emissions is evident in the spectrum of the amplified spontaneous emission at 177 kW/cm^2 shown in Fig. 5. Under high levels of excitation, band filling can result in a widening of the gain profile and less dramatic narrowing of the lasing spectra near the threshold. A similar lack of narrowing in the lasing spectra at threshold is also found in photopumped Be-chalcogenide-based single quantum-well lasers[9] in which high levels of excitation and band filling are expected due to lack of waveguide structure for optical confinement. The green lasing emission occurs at 514 nm with a similar behavior as a function of excitation intensity.

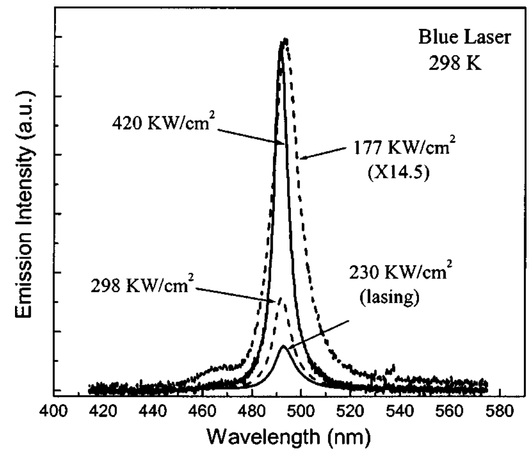

FIG. 5. Spectra of blue laser emission at different excitation intensities operated at room temperature. (The spectrum at pumping intensity of 177 kW/cm^2 is amplified by 14.5 times in order to see clearly the emission from barrier.)

The temperature dependent threshold pumping intensity measurements for this laser structure are shown in Fig. 6. The inset of Fig. 6 shows the emission intensity as a function of excitation intensity at elevated temperature varying from 288 to 348 K. Clear threshold behavior is observed up to 348 K. T_0 is estimated to be 35 K from an exponential rela-

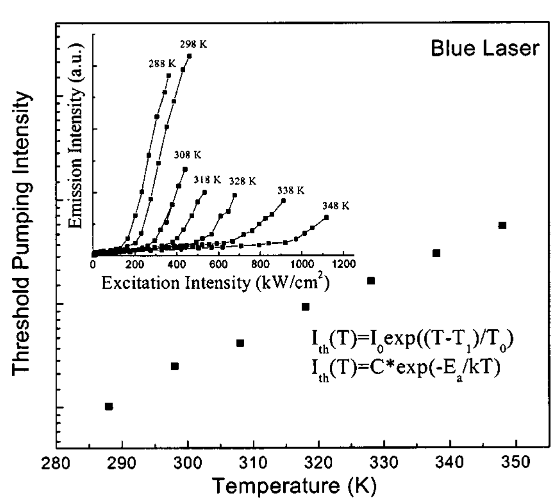

FIG. 6. Temperature dependence of the lasing threshold for blue laser structure. Lasing is observed up to 348 K and T_0 is estimated to be 35 K.

tionship between threshold and temperature by an empirical formula shown in Fig. 6, where I_0 is the threshold at an arbitrary reference temperature T_1, T is the absolute temperature, and T_0 is the characteristic temperature often used to express the temperature sensitivity of threshold. The temperature dependent threshold pumping intensity measurements have also been done for the green laser and in that case T_0 has been estimated to be 60 K. Previous studies of III–V AlGaAs lasers and InGaAsP lasers show that the value of T_0 is affected by the carrier recombination mechanisms[10,11] such as Auger recombination and carrier confinement.[12,13] Since higher band gap results in smaller Auger coefficient, weak carrier confinement is believed to be the reason for the low T_0 in our $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se/Zn_xCd_yMg_{1-x-y}Se$ SQW blue laser structure compared to the green laser structure. The temperature dependency of the threshold pumping intensity can be fitted by a simple Arrhenius relation $I_{th}(T)=C^* \exp(-E_a/kT)$ with an activation energy $E_a=250\pm4$ meV where C is a parameter depending on electron diffusion coefficient and electron effective mass, etc.. This activation energy is very close to the band gap difference of 259 meV between the cladding and the QW in the conduction band assuming $\Delta E_c/\Delta E_v=70/30$ where ΔE_c and ΔE_v are the barrier height in the conduction and valence band, respectively. This points to a carrier loss process involving thermalization of electrons into the cladding layer and subsequent diffusion away from the quantum well. Similar carrier loss was found in AlGaInP-based laser diodes emitting at 633 nm.[14] The T_0 value may be increased by using multiple-quantum-well active region and by improving the carrier confinement between the cladding layer and the QW through changing the cladding layer composition or using artificial "multi-quantum barriers."[15,16]

In summary, laser structures containing a quaternary $Zn_xCd_yMg_{1-x-y}Se$ SQW embedded in a waveguide consisting of two 0.1-μm-thick $Zn_{x'}Cd_{y'}Mg_{1-x'-y'}Se$ layers and $Zn_xCd_yMg_{1-x-y}Se$ as cladding layers have been grown. These structures are closely lattice matched to the InP substrate and have a good quality indicated by narrow (004) DCXRD curves and narrow PL linewidths at 77 K. We have achieved optically pumped blue lasing at 492 nm and green lasing at 514 nm at room temperature from two SQW laser structures with relatively thick quaternary QWs. The lasing linewidth was ~5 nm. The lasing threshold pumping intensity has been measured to be ~220 kW/cm^2 for the blue laser and ~160 kW/cm^2 for the green laser at room temperature. The T_0 was estimated based on the temperature dependency of the threshold pumping intensity. Values of T_0 of ~35 K and ~60 K were obtained for the blue and green laser, respectively. The higher threshold pumping intensity and lower T_0 value for the blue laser can be ascribed to its shallower carrier confinement. The temperature dependency of the threshold pumping intensity can be fitted by a simple Arrhenius relation $I_{th}(T)=C^* \exp(-E_a/kT)$ with an activation energy E_a very close to the band gap energy difference between the cladding layer and the quantum well in the conduction band. This points to a carrier loss process through thermalization into the cladding layer and subsequent diffusion away from the quantum well.

ACKNOWLEDGMENTS

One of the authors (X. Zhou) would like to thank Yi Gu (Columbia University) for his assistance in fabricating the lasers. Support from the New York Science and Technology on Photonic Materials and Applications and from the Center for Analysis of Structures and Interfaces is greatly appreciated.

[1] M. C. Tamargo, A. Cavus, L. Zeng, N. Dai, N. Bambha, A. Gary, F. Semendy, W. Krystek, and F. H. Pollak, J. Electron. Mater. **25**, 259 (1996).
[2] A. Cavus, L. Zeng, M. C. Tamargo, N. Bambha, F. Semendy, and A. Gary, Appl. Phys. Lett. **68**, 3446 (1996).
[3] L. Zeng, B. X. Yang, A. Cavus, W. Lin, Y. Y. Guo, M. C. Tamargo, Y. Guo, and Y. C. Chen, Appl. Phys. Lett. **72**, 3136 (1998).
[4] M. C. Tamargo, W. Lin, S. P. Guo, Y. Luo, Y. Guo, and Y. C. Chen, J. Cryst. Growth **214/215**, 1058 (2000).
[5] S. P. Guo, L. Zeng, and M. C. Tamargo, Appl. Phys. Lett. **77**, 1 (2001).
[6] L. Zeng, S. P. Guo, Y. Y. Luo, M. C. Tamargo, H. Xing, and G. S. Cargill III, J. Vac. Sci. Technol. B **17**, 1255 (1999).
[7] C. A. Zmudzinski, Y. Guan, and P. S. Zory, IEEE Photonics Technol. Lett. **2**, 94 (1990).
[8] L. Zeng, B. X. Yang, and M. C. Tamargo, Appl. Phys. Lett. **72**, 1317 (1998).
[9] J. H. Chang, M. W. Cho, K. Godo, H. Makino, T. Yao, M. Y. Shen, and T. Goto, Appl. Phys. Lett. **75**, 894 (1999).
[10] T. R. Chen, B. Chang, L. C. Chiu, K. L. Yu, S. Margalit, and A. Yariv, Appl. Phys. Lett. **43**, 217 (1983).
[11] L. C. Chiu, K. L. Yu, S. Margalit, T. R. Chen, U. Koren, A. Hasson, and A. Yariv, IEEE J. Quantum Electron. **QE-19**, 1335 (1983).
[12] G. H. B. Thompson, Proc. IEEE **I128**, 37 (1981).
[13] A. Sugimura, IEEE J. Quantum Electron. **QE-17**, 441 (1981).
[14] D. P. Bour, D. W. Treat, R. L. Thornton, R. S. Geels, and D. F. Welch, IEEE J. Quantum Electron. **29**, 1337 (1993).
[15] K. Kishino, A. Kikuchi, Y. Kaneko, and I. Nomura, Appl. Phys. Lett. **58**, 1822 (1991).
[16] T. Fukushima, H. Shimizu, K. Nishikata, Y. Hirayama, and M. Irikawa, Appl. Phys. Lett. **66**, 2025 (1995).