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Red–green–blue photopumped lasing from ZnCdMgSe/ZnCdSe quantum well laser structures grown on InP

L. Zeng, B. X. Yang,[a] A. Cavus,[b] W. Lin, Y. Y. Luo, and M. C. Tamargo[c]
Department of Chemistry, City College of City University of New York, New York, New York 10031

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

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Room-temperature optical pumped lasing emission in the red, green, and blue has been obtained from ZnCdMgSe/ZnCdSe quantum well (QW) laser structures grown on InP substrates. The structures are nearly identical, except for variations in the thickness and/or composition of the QW layer. No other single set of semiconductor materials has been demonstrated whose structures are pseudomorphic on one single substrate, and produces light emitters throughout the entire visible range. Our results demonstrate the potential for these materials as integrated full color display devices. © *1998 American Institute of Physics.* [S0003-6951(98)02524-8]

Semiconductor lasers and light emitting diodes (LEDs) that emit in the visible range have potential applications in full color displays and high density digital recording. Currently used LED-based full color display panels use different materials on different substrates as the three primary colors: red, green, and blue (R–G–B). In order to fabricate integrated systems, it is of interest to find a single material grown on a single substrate that can be used for the full color range. For the green and blue lasers, room-temperature continuous wave (cw) blue lasers made from ZnSe based II–VI materials grown on GaAs substrates[1] and from GaN materials[2] have been reported, while red lasers are available from GaP based III–V materials.[3] It would be difficult to combine these materials into a single substrate for device integration, so it is of interest to explore new materials that may be used to design structures from compatible materials that can be grown in high quality on a single substrate, and that also meet the band structure requirements of these complex devices.

Wide band gap (Zn,Cd,Mg)Se is a new quaternary materials system that can be used in the design and fabrication of R–G–B full color displays.[4,5] These layers can be grown lattice matched to InP substrates with a wide range of band gaps, from 2.18 to ~3.5 eV. By using ZnCdMgSe layers as cladding and waveguiding layers and a ZnCdSe layer as the active layer, we can design totally lattice-matched or pseudomorphic laser structures with emission ranging throughout the entire visible range, from blue to red. These structures grown on InP substrates also allow the growth of a symmetrically strained ZnSe/ZnTe superlattice or lattice-matched ZnSeTe alloys that may be easily doped *p* type for the ohmic contact without introducing defects due to lattice mismatch.[6,7] Thus red, green, and blue emission can be achieved from almost identical structures where only the quantum well (QW) thickness and /or composition are varied. In this letter, we will summarize the results of the growth of ZnCdSe and ZnCdMgSe and report the results of optically pumped lasing of ZnCdMgSe/ZnCdSe QW laser structures grown lattice matched to InP substrates with emission that ranges from blue to red. These materials are excellent candidates for integrated full color display devices.

A schematic of a separate confinement heterostructure single QW laser structure grown lattice matched to InP substrates is shown in Fig. 1(a). The right-hand side shows the band gap profile. The layers were grown by molecular beam

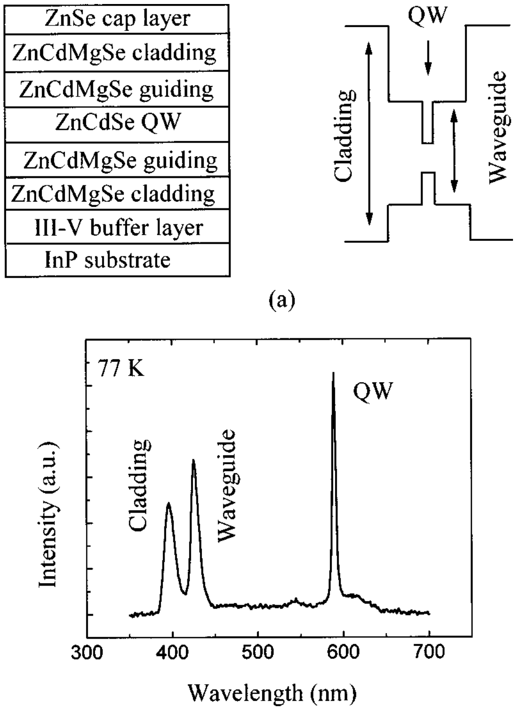

FIG. 1. The layer structure and the band gap profile of a separate confinement heterostructure single QW laser grown lattice matched to InP substrates (a) with a typical 77 K photoluminescence spectrum (b).

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[a] Current address: Fujitsu Compound Semiconductor, Inc., 2355 Zanker Rd., San Jose, CA 95131-1136.

[b] Current address: TRW, One Space Park, Redondo Beach, CA 90278.

[c] Electronic mail: tamar@scisun.sci.ccny.cuny.edu

epitaxy (MBE) in a Riber 2300P system which includes a III–V chamber and a II–VI chamber connected by ultrahigh vacuum. Prior to use, the InP(001) substrates were degreased and etched as previously described.[4,5] Oxide desorption of the InP substrates was performed in the III–V chamber by heating to ~490 °C with an As flux impinging on the InP surface. A lattice-matched InGaAs buffer layer (~0.2 μm) was grown and the substrate with the buffer layer was transferred to the II–VI chamber. Growth of the II–VI material was performed under Se-rich conditions with a VI/II beam equivalent pressure ratio of ~4. The growth was initiated at a low temperature of 170 °C by growing a ~50 Å ZnCdSe interfacial layer. After 1 min of growth, the temperature was raised to a growth temperature of 270 °C with a 4 min interruption, after which the structure was grown. The thickness and the composition of the ZnCdSe QW are chosen according to the desired emission range. In the range from blue to yellow, a lattice-matched composition with a nominal band gap of 2.2 eV was used. The emission range was tuned by changing the ZnCdSe QW thickness. In the red range, a lattice-mismatched (1.2%) ZnCdSe QW layer with a thickness of 100 Å was used. The QW was embedded in a waveguide consisting of two 0.2-μm-thick ZnCdMgSe layers with nominal band gaps of ~2.7 eV. The cladding layers were 0.5-μm-thick ZnCdMgSe layers with nominal band gaps of ~3.0 eV. A 10 nm ZnSe cap layer was used to protect the top cladding layer from oxidation. The waveguide and cladding layers were grown without doping and have less than 0.2% mismatch to the InP substrates.

The samples were characterized by low temperature photoluminescence (PL) at 77 K and (400) double crystal x-ray diffraction (DCXRD).[8] They were thinned to about 100 μm thickness and cleaved into 1-mm-wide bars for photopumping. The experimental setup for photopumping was similar to that described in Ref. 9. A frequency tripled Nd:YAG laser pumped dye laser was used as the pump source. The pulse width and repetition rate of dye laser output were 7 ns and 20 Hz, respectively. To ensure the largest concentration of photogenerated carriers in the vicinity of the QW, the wavelength of the dye laser was tuned to the photon energy near the band gap of the waveguide layer at room temperature. The pump 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 analyze the spectral characteristics. A boxcar integrator was used to measure the pumping power and output light power.

In order to grow the laser structure, it is important to establish the appropriate growth conditions for the QW, waveguide, and cladding layers lattice matched to InP substrates. Figure 2 shows the relationship between the band gap of (Zn, Cd, Mg)Se layers at 77 K and the percent of lattice mismatch to the InP substrates ($\Delta a/a \times 100$). The lattice-matched position is indicated by a vertical dashed line. The three solid squares represent the positions of binary materials ZnSe, CdSe, and MgSe. The solid line represents the empirical fit to the ZnCdSe data reported in the literature.[10] The data points were obtained for 1-μm-thick $Zn_xCd_yMg_{1-x-y}Se$ and $Zn_xCd_{1-x}Se$ layers. The single layers were grown under the same conditions as those of the laser structures. The band gaps are obtained from the 77 K PL data. As can be seen, lattice-matched ZnCdSe layers have a band gap of 2.18 eV at 77 K, corresponding to ~2.09 eV at room temperature, in the yellow range. By adding Mg and adjusting the Cd/Zn ratio to grow the ZnCdMgSe quaternary layers, the lattice mismatch can be controlled to <0.2% while the band gap can vary from 2.18 to ~3.3 eV, corresponding to the range from yellow to blue. As previously shown, below 3.1 eV, the quality of the ZnCdMgSe layers is independent of the Mg fraction (band gap) and is equivalent to that of ZnCdSe ternary layers.[8] The defect densities are in the range of $\sim 10^6$ cm^{-2}, and the full widths at half maximum (FWHM) of DCXRD are <100 arcsec. Attempts to further increase the band gap by increasing the Mg fraction resulted in layers for which the reflection high energy electron diffraction (RHEED) pattern gradually degraded, becoming spotty as the growth progressed. Also shown on Fig. 2 is the data point (triangle) for a thick mismatched ($\Delta a/a = 1.2\%$) ZnCdSe layer. The corresponding band gap is ~2.03 eV in the red range.

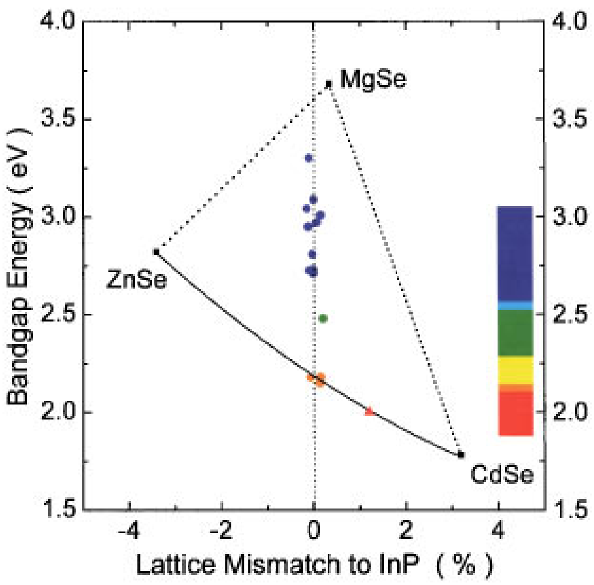

FIG. 2. The relationship between the band gap of (Zn, Cd, Mg) Se layers at 77 K and the percent of lattice mismatch to the InP substrates. The data points were obtained from ZnCdMgSe (blue and green solid circles) and ZnCdSe (orange solid circles and red solid triangle).

We have grown several laser structures for optical pumping. Table I shows the parameters of three such structures. The QW emission wavelengths were obtained from the 77 K PL. The QW mismatch was estimated from x-ray measurements of a 1-μm-thick reference layer grown under the same growth conditions as the QW. The QW thickness was

TABLE I. Parameters of three laser structures with emission from blue to red.

Sample	QW thickness (nm)	QW mismatch (%)	QW emission wavelength at 77 K (nm)
A	2.8	~0	473
B	4.0	~0	516
C	12.0	1.2	590

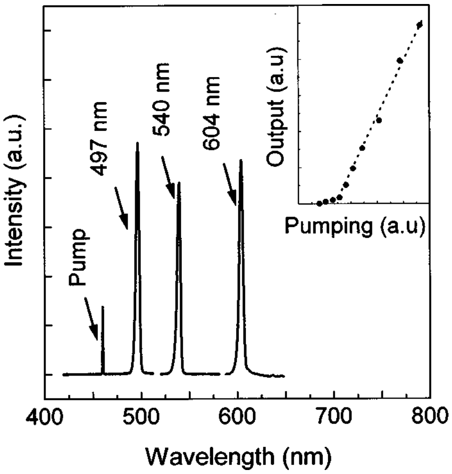

FIG. 3. The laser emission from three ZnCdSe/ZnCdMgSe laser structures grown on InP substrates with emission wavelengths from 497 to 604 nm, covering the range from blue to red. The inset shows typical turn on characteristics obtained with one of these structures.

calculated from the growth time of the QW and the growth rate of the reference sample. By using lattice-matched ZnCdSe layers and changing the QW thickness (samples A and B), the emission range was varied from yellow to near blue. By using a strained ZnCdSe layer as the QW (sample C), the emission of the QW was in the red. Figure 1(b) shows the 77 K PL spectrum for structure C. These data show that the range over which we can vary the QW emission wavelength is as high as 700 meV.

Optical pumping was performed for the three structures of Table I. Figure 3 shows the above threshold lasing spectra. The pumping wavelength is $\sim$460 nm. The laser emission wavelengths obtained at room temperature are 497, 540, and 604 nm for samples A, B, and C, respectively, covering the range from near blue to red. The stimulated emission peaks have a typical linewidth of about 5 nm, which is about a factor of 5 less than the spontaneous emission peaks. The inset in Fig. 3 shows typical turn on characteristics obtained with one of these structures. The relationship between the output intensity and the pumping intensity exhibited a typical superlinear relation below the lasing threshold and a linear relation above the threshold. Thus, stimulated emission in the blue, green, and red has been obtained from these three nearly identical ZnCdSe/ZnCdMgSe structures grown on InP substrates. This result demonstrates the potential for fabricating integrated full color display elements from these materials. To date, as far as we know, no other single set of semiconductor materials has been demonstrated whose structures are pseudomorphic on one single substrate, and produces light emitters operating throughout the entire visible range.

In conclusion, we have reported room-temperature photopumped lasing from three ZnCdMgSe/ZnCdSe laser structures grown on InP. The structures are nearly identical, except for variations in the thickness and/or composition of the QW layer. Lasing emission in the red, green, and blue region was obtained. Our results demonstrate the potential for these materials as integrated full color display devices.

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