Photo-pumped ZnCdSe/ZnCdMgSe blue-green quantum well lasers grown on InP substrates

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We report the operation of new photo-pumped blue-green ZnCdSe/ZnCdMgSe graded-index separate confinement heterostructure single quantum well lasers grown lattice matched on InP substrates. Laser emission at 512 nm was observed. The T_0 value is 150 K at room temperature. These materials are proposed as alternative materials for the fabrication of visible semiconductor lasers. © *1997 American Institute of Physics.* [S0003-6951(97)00811-5]

In the last few years, the development of ZnSe based blue-green semiconductor lasers has attracted a great deal of interest. Following the seminal breakthrough in doping technology, continuous operation of II-VI semiconductor lasers at room temperature has been demonstrated. To date, the blue-green lasers are based on $Zn_xCd_{1-x}Se$ quantum well materials and are grown on GaAs substrates. In this material system, although the cladding and waveguiding layers are grown lattice matched to the substrate, a large lattice mismatch exists between the $Zn_xCd_{1-x}Se$ epitaxial layers and GaAs. The large lattice mismatch produces strain which often affects the quality of the material and may result in early degradation of the laser device during operation. One of the possible causes of rapid degradation of the device is dark line defects forming in the active layer from pre-existing defects of the material.[1,2] The presence of strain in the active region may assist or promote defect propagation and dark line formation.

On the other hand, recent progress[3–5] on ternary ZnCdSe and ZnSeTe and quaternary ZnCdMgSe materials grown on InP substrates points to an alternative for the blue-green lasers. The use of InP as the substrate material makes it possible to select among a set of new II-VI quaternary and ternary materials for the quantum well, waveguide, and cladding layers that can be all lattice matched to the substrates. This offers great promise in terms of improved crystalline quality and reliability over the II-VI materials that have previously been used to fabricate blue-green lasers. In addition, the room temperature bandgap for the ZnCdMgSe quaternary system ranges from 2.1 eV to well over 3 eV. Thus, in lattice matched ZnCdSe/ZnCdMgSe quantum well structures, by controlling the thickness of the quantum well, the emission wavelength can be made to vary over a wide spectral range from yellow to blue.[6] This feature allows lasers that emit over most of the visible range to be fabricated from these materials and has potential practical applications.

In this letter, we report the operation at room temperature of a new blue-green ZnCdSe/ZnCdMgSe graded-index separate confinement heterostructure single quantum well laser grown lattice matched to InP substrates. The schematic of the layer structure, bandgap profile and expected refractive index profile of the laser material are illustrated in Fig. 1. The epitaxial layers were grown by molecular beam epitaxy (MBE). The substrates were commercially available (100) InP substrates. The light emitting region was a 4 nm single $Zn_xCd_{1-x}Se$ quantum well with a nominal bandgap of 2.2 eV. The quantum well (QW) was embedded in a graded-index waveguide consisting of two 0.2 μm graded composition $Zn_xCd_yMg_{1-x-y}Se$ layers in which the nominal bandgap varied continuously from 2.7 to 3.0 eV. The cladding layers were 1 μm-thick quaternary $Zn_xCd_yMg_{1-x-y}Se$ with a nominal bandgap of 3.0 eV. A 10 nm ZnSe cap layer was used to protect magnesium in the cladding layer from oxidizing. All layers were undoped. The refractive index profile of the waveguide structure, shown in Fig. 1(c), was constructed by assuming a refractive index versus bandgap energy relation of -0.7/eV for the ZnMgSSe/GaAs system.[7] The optical confinement factor for the fundamental transverse mode calculated with finite element computer analysis is 1.39%. The sample was thinned to about 100 μm thickness and cleaved into 1-mm-wide bars for photo-pumping.

To characterize the layer structure we performed 77 K photoluminescence (PL) measurements. The results are shown in Fig. 2. The 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 detector. The PL was measured on the as-grown wafer (trace a) and on a sample of the wafer that has been etched with dilute bromine methanol solution to remove about 0.8 μm from the surface (trace b). The strongest emission observed from the as-grown sample is at 405 nm (peak 1) and corresponds to the bandgap energy of the top cladding quaternary layer. Since most of the light is absorbed near the surface, emission from the underlying layers is expected to be weak. In fact, weak emissions are also seen at 420 and 490 nm, the energies expected from recombination at the bottom of the graded waveguide region (peak 2) and the QW (peak 3), respectively. Upon etching most of the 1-μm-thick cladding layer (trace b) the intensities of the two lower energy peaks, in particular that attributed to the QW emission (peak 3),

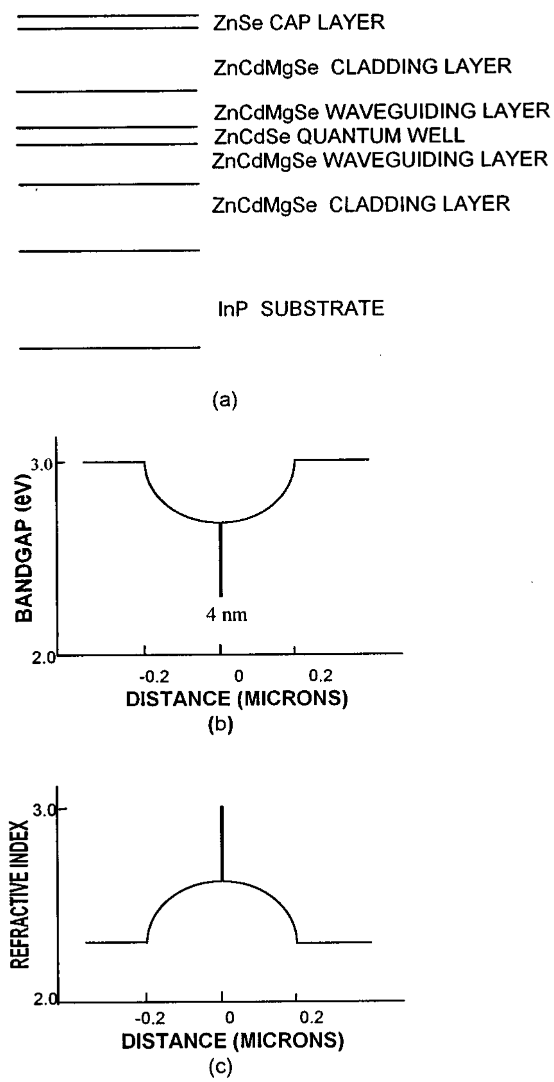

FIG. 1. Schematics of the (a) layer structure, (b) bandgap profile, and (c) refractive index profile of the graded-index separate confinement single quantum well laser.

increase dramatically, clearly confirming the presence of high quality QW and waveguiding layers.

The experimental setup for photo-pumping was similar to that described in Ref. 8. 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 photo-generated carriers in the vicinity of quantum well, the wavelength of the dye laser was tuned to 460 nm, corresponding to the photon energy near the bandgap of the bottom of the graded-index waveguide 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.

Figure 3 shows the output intensity from the single quantum well laser as a function of pumping intensity. The

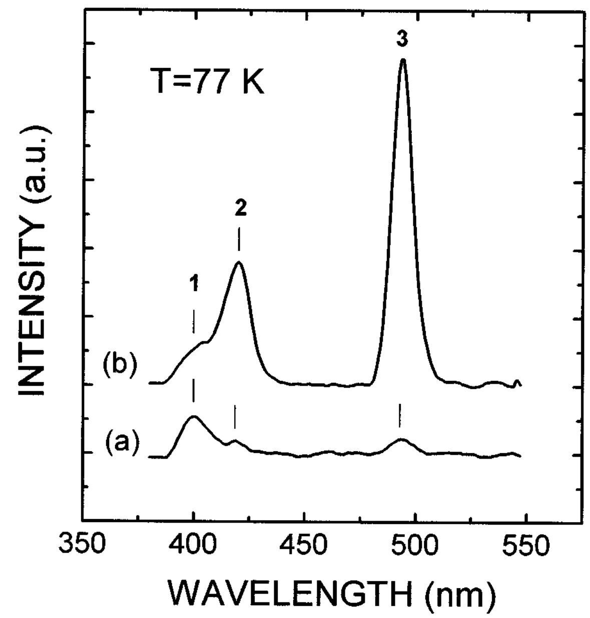

FIG. 2. Photoluminescence spectra at 77 K of the ZnCdSe/ZnCdMgSe quantum well layered structure. Trace (a) is measured on the as-grown surface while trace (b) is measured on a sample that was etched in bromine methanol to remove ~0.8 μm of the top layer. Peaks labeled 1, 2, and 3 are assigned to the cladding, waveguide, and quantum well layers, respectively.

output-input plot exhibited a typical superlinear relation below the lasing threshold and a linear relation above the threshold. The threshold occurs at a pumping power density of 160 kW/cm^2. The threshold value increases by 35% as the temperature is raised from 2 to 47 °C. From the temperature dependency of the threshold power density, the T_0 value is 150 K, which is comparable to previously reported values for (Zn,Cd)Se/ZnMgSSe lasers.[9,10] Shown in Fig. 4 are the spectra of the edge emission below threshold and above the lasing threshold at two different pumping powers. The onset of

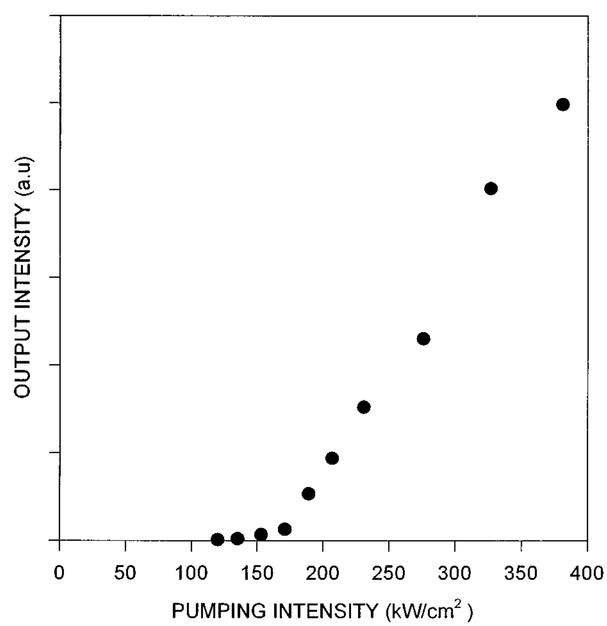

FIG. 3. Output intensity vs pumping intensity at room temperature. The threshold excitation intensity is estimated to be 160 kW/cm^2.

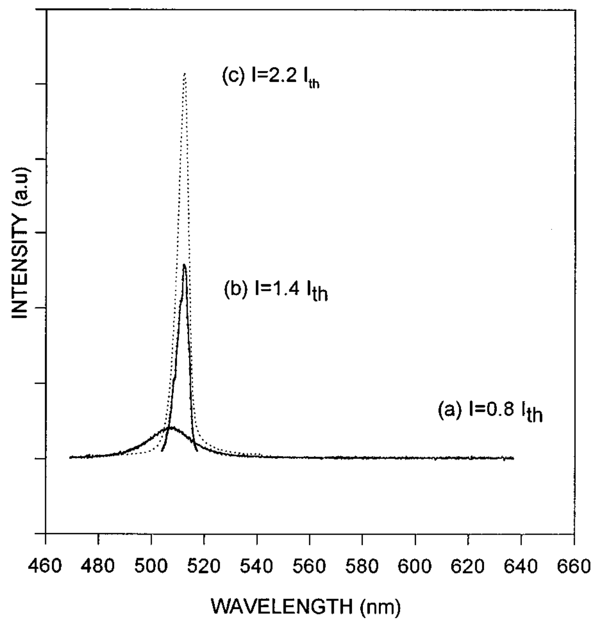

FIG. 4. Spectra of edge emission below threshold and above lasing threshold, at two different pumping powers, measured at room temperature. The instrument resolution is 0.05 nm.

laser oscillation at 512 nm is accompanied by a narrowing of the spectrum. Both the turn-on characteristics of the power curve (Fig. 3) and the width of the stimulated emission line (Fig. 4) are qualitatively very similar to the behavior of ZnSe/ZnMgSSe laser previously reported.[10] A linewidth narrowing of about four times was observed above the threshold. The resolution of the optical multichannel analyzer is about 0.05 nm. The lasing linewidth, about 5 nm, is broader than observed in other materials. The cause of the relatively broader lasing linewidth is under current investigation. Other laser parameters such as the differential quantum efficiency cannot be quantified since the absorption coefficients at the pumping wavelength for these materials are not known. This also prevented us from making quantitative comparison of the performance between the step- and graded-index structures.

Since the parameters for this new material system, such as the effective masses, band offsets, and refractive indices, are not well characterized, no attempt has been made to optimize the device performance in the present study. However, improvement can be made in both material quality and laser structure. Our analyses indicate that significant reduction in lasing threshold can be made by using an improved graded-index waveguide. For example, the optical confinement factor of the graded-index waveguide can be increased by 50% if the thicknesses of the graded composition layers are reduced to 0.1 μm while keeping a constant range of composition variation. Regarding the material quality, the incorporation of a III-V buffer layer on the InP substrate prior to II-VI deposition has been shown to improve dramatically the crystalline quality of the II-VI materials.[11] This addition is likely to reduce the interface roughness between the layers, also contributing to improved laser properties.

In summary, we report the demonstration of room temperature photo-pumped blue-green laser oscillation in new ZnCdSe/ZnCdMgSe quantum well lasers grown lattice matched to InP substrates. These new materials represent an alternative to the currently used ZnSe based materials for blue-green lasers, grown on GaAs. The absence of strain in this structure should contribute to improved reliability of the devices.

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