Patterned three-color ZnCdSe/ZnCdMgSe quantum-well structures for integrated full-color and white light emitters

Y. Luo,[a)] S. P. Guo, O. Maksimov,[a)] and M. C. Tamargo[a),b)]
Department of Chemistry, City College of the City University of New York, New York, New York 10031

V. Asnin and F. H. Pollak[a)]
Department of Physics, Brooklyn College of the City University of New York, Brooklyn, New York 11210

Y. C. Chen[a)]
Department of Physics, Hunter College of the City University of New York, New York, New York 10021

(Received 8 August 2000; accepted for publication 12 October 2000)

We report the growth and characterization of patterned ZnCdSe/ZnCdMgSe quantum-well (QW) structures grown adjacent to each other on a single InP substrate. Each structure emits at a different wavelength range spanning the visible range. Stripe and square-shaped QW structures of different emission wavelengths, with lateral dimensions between 15 and 60 μm, were deposited sequentially by shadow mask selective area epitaxy (SAE) steps. Conventional and microphotoluminescence measurements were used to characterize the patterned QWs. They exhibit well-defined excitonic emission in the red, yellow, and green regions of the visible spectrum. This result demonstrates the feasibility of fabricating integrated full-color light emitting diode and laser-based display elements and white light sources using the ZnCdMgSe material system and shadow mask SAE. © *2000 American Institute of Physics.* [S0003-6951(00)04149-8]

Light emitting diodes (LEDs) and laser diodes (LDs) having emission in the red-green-blue ($R-G-B$) are of interest for fabrication of full color displays. Current semiconductor technology requires the use of discrete devices of different materials, which provide emission in the three regions of the visible spectrum, to be fabricated separately and then combined into a display unit.[1] This implies the need for different materials growth capabilities and separate device fabrication sequences appropriate for the materials used. Such complexity limits the possibility of fabricating practical LED or laser based full color displays. Identifying a single material system to produce the $R-G-B$ emissions is highly desirable and would greatly simplify the fabrication process. Grown on a single substrate would enable *integration and miniaturization* of the $R-G-B$ emitters during the growth sequence adding appeal to this technology.

Wide band gap (Zn, Cd, Mg)Se is a quaternary material system that may satisfy the requirements described earlier and thus has potential applications in semiconductor display technology. By using $Zn_xCd_yMg_{1-x-y}Se$ layers of different band gaps (i.e., compositions) as the cladding and waveguiding layers and a $Zn_xCd_{1-x}Se$ layer as an active layer, we can design totally lattice matched or pseudomorphic LD and LED structures with emission that can be adjusted throughout the entire visible spectrum, from blue to green to red.[2] A lattice matched highly *p*-type doped ZnSeTe alloy can also be grown on these structures to be used as an ohmic contact layer, without introducing defects due to lattice mismatch.[3] Thus, $R-G-B$ emission can be achieved from almost identical structures where only the ZnCdSe quantum well (QW) thickness and/or composition are varied. We have fabricated optically pumped $R-G-B$ lasers based on this material system.[2] LEDs emitting at different wavelengths throughout the visible range have also been achieved.[4] Therefore, the fabrication of integrated monolithic full-color display devices can be considered by simply combining three color ($R-G-B$) ZnCdSe/ZnCdMgSe QW structures on one substrate. White light sources could also be achieved by this approach. Recently, $R-G-B$ emission from rare earth doped GaN-based structures has been reported.[5] The defect-related emission (nonexcitonic) of those structures, although adequate for LED applications, is not appropriate for semiconductor laser operation.

Shadow mask selective area epitaxy (SAE) is a technique for mechanically masking the surface area selectively and growing desired layers and structures over the exposed regions.[6] It is a feasible approach for the monolithic integration of different device structures on the same substrate. It has been shown that by using a susceptor design in metalorganic chemical vapor deposition that allows relative motion between a GaAs substrate and a GaAs mask, GaAsP and GaAs based multiple detectors with different cutoff wavelengths and multiple color LEDs can be integrated on a single GaAs substrate.[7] Monolithic integration of multiple wavelength vertical-cavity surface emitting lasers has been reported using a moveable shadow mask during molecular beam epitaxy (MBE) growth.[8] We have recently demonstrated shadow mask SAE for the growth of CdTe detector array-like structures.[9]

In this letter, we report the MBE integration and characterization of ZnCdSe/ZnCdMgSe QWs with three different emission wavelengths that span most of the visible range grown by sequential shadow mask SAE. Conventional photoluminescence (PL) measurements were performed to char-

[a)]Also at: the Graduate School and University Center of CUNY, New York, NY 10016.
[b)]Electronic mail: tamar@scisun.sci.ccny.cuny.edu

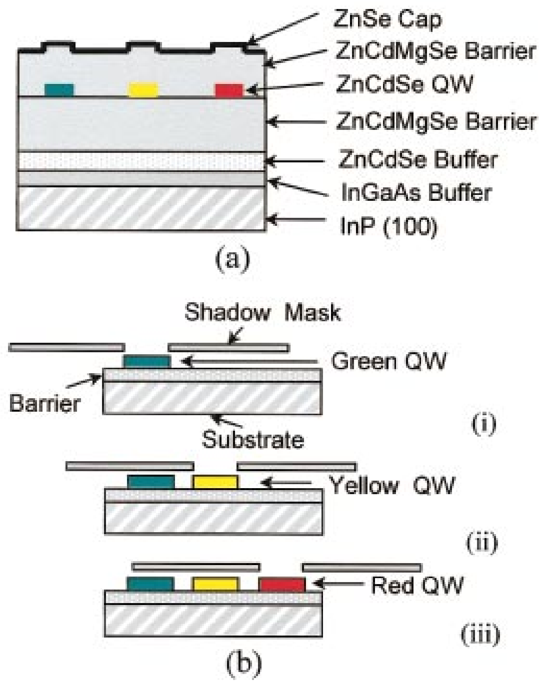

FIG. 1. (Color) (a) Schematic of the integrated (monolithic) three-color quantum well structure grown. (b) Illustration of the sequential step SAE process used.

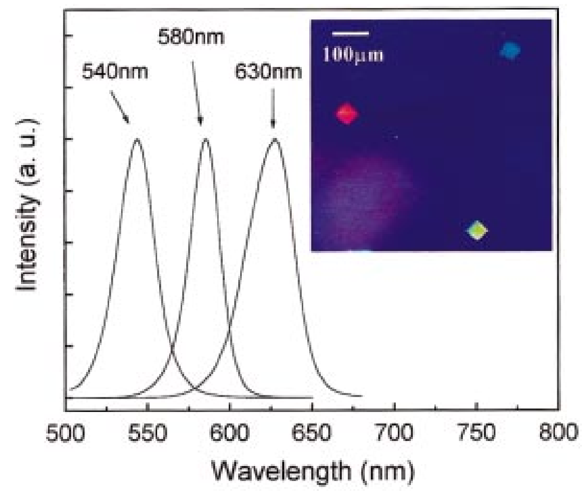

FIG. 2. (Color) Room temperature micro-PL spectra of three patterned QW regions grown on a single InP substrate. The inset is a photograph of the surface PL emission. The QWs are patterned to form three small squares each emitting at a different wavelength, one red, one yellow, and one green.

acterize these patterned QW structures. Well-defined emission in the red, yellow, and green was observed from the different patterned regions.

The growth was performed by shadow mask SAE in a Riber 2300P MBE system that consists of two growth chambers connected by ultrahigh vacuum (UHV) modules. One chamber is dedicated to the growth of II–VI materials and the other to III–Vs. A specially designed mask and mask fixture were used to perform this work.[9] The mask fixture allows the mask to be placed and removed from the substrate within the vacuum growth system so that multiple SAE steps can be performed sequentially. The structures were grown on semi-insulating InP(100) substrates that were deoxidized in the III–V chamber under an As overpressure. A lattice-matched InGaAs buffer layer was grown under conventional MBE growth conditions to improve surface morphology. The sample was then transferred to the II–VI chamber in UHV, where a ~10 nm ZnCdSe low-temperature (LT) buffer layer was grown at 170 °C.[10] The Zn and Cd fluxes had previously been adjusted to calibrate the composition of the ZnCdMgSe and ZnCdSe layers so that they were lattice matched to the InP substrate and had the desired band gap. The ZnCdSe LT buffer layer was followed by a 0.5-μm-thick ZnMgCdSe barrier layer grown at 250 °C with a band gap of 2.8 eV. The three patterned ZnCdSe/ZnCdMgSe QWs were then grown sequentially on the different areas of the barrier layer using the multiple-step SAE process described later. Two ZnCdSe QWs, nominally 2 and 6 nm, were grown lattice-matched to InP to produce emission in the blue and green regions. The third QW, nominally 10 nm thick, was grown with a higher Cd concentration ($\Delta a/a$ of ~1.8% to InP) in order to obtain red emission. A schematic of the full structure grown is shown in Fig. 1(a).

Figure 1(b) illustrates the application of sequential shadow mask SAE for the QW integration. After the growth of the buffer layers and the flat ZnCdMgSe bottom barrier layer, the shadow mask is placed and one set of patterned ZnCdSe QW is grown (i). The mask can then be moved relative to the substrate and the second set of patterned ZnCdSe QW is deposited adjacent to the first one (ii). The third ZnCdSe QW can be grown in the same manner, after the second one (iii). The mask can then be removed and the top ZnCdMgSe barrier layer can be grown over the entire surface. In this way, regions with different color QWs are combined (i.e., integrated) on a single substrate. A uniform ZnSe cap layer of ~6 nm thick is grown to protect the ZnCdMgSe layer from oxidation.

Micro-PL measurements were performed to characterize these integrated ZnCdSe/ZnCdMgSe patterned QWs. The measurement was done using a triple grating micro-Raman/PL spectrometer (JY-64000). The 488 nm line of an argon ion laser was used as excitation with spot size of 2–3 μm. Figure 2 shows the room temperature micro-PL spectra obtained from three patterned QW regions having different emission wavelengths. The peaks are centered at around 544, 585, and 628 nm with full widths at half maxima of 24, 19, and 29 nm, respectively. The relative intensities from the three QWs are similar, indicating that the QWs are of comparable quality. This implies that the quality of the QW region grown first does not degrade during the growth interruption, the multiple mask replacements and the deposition steps needed to grow the other two QWs. The variation in linewidth of the three regions is consistent with the different QW layer properties. The broader emission line is obtained from the red QW, which is highly strained and possibly partially relaxed. By adjusting the ZnCdSe composition and the thickness, a pseudomorphic QW can be designed for emission at this wavelength.[11] The other two QWs are lattice matched and thus have narrower linewidths. Of the two, the yellow QW is the thicker one, which results in a narrower emission spectrum due to the reduced effect of thickness fluctuations and interface roughness. Based on the PL emission wavelengths obtained we conclude that the actual QW thickness obtained were somewhat larger than intended. Blue

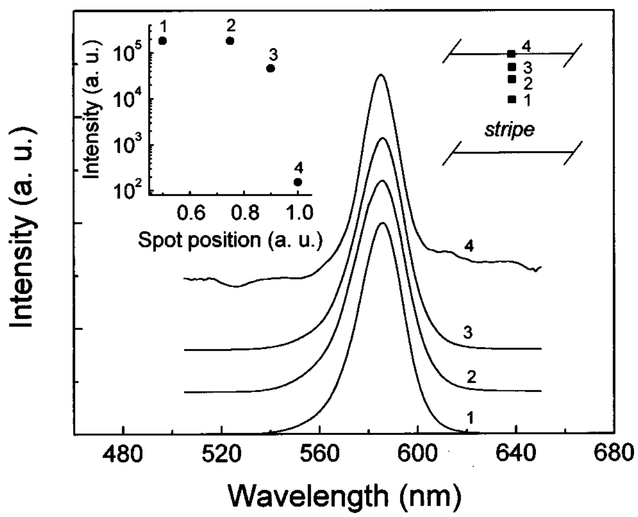

FIG. 3. Room temperature micro-PL spectra taken at four different positions in a patterned QW stripe. The positions are indicated schematically in the right-side inset. The left-side inset shows the relative intensities of the PL emission at the four positions.

emission can be obtained by growing a thinner lattice-matched ZnCdSe QW layer.[12]

The inset of Fig. 2 is a photograph of the sample surface that shows three square-shaped ZnCdSe QW patterned regions emitting at different wavelengths, located near each other on the InP substrate. It was taken by a conventional photographic camera, observing through a microscope objective for magnification, while the sample surface was exposed to the excitation laser (frequency-tripled Nd:yttrium–aluminum–garnet laser at 355 nm) in a conventional PL setup, thus the color seen is the color of the PL emission. The squares are about 50 μm$\times$50 μm and they are separated by $\sim$500 μm from each other. Each of the squares exhibits different emission wavelength range: one in the red, one in the yellow, and one in the green. The slightly distorted colors of the three squares (compared to the spectra shown in Figs. 2 and 3) are most likely due to artifacts caused by the exposure of the film.

The lateral thickness and compositional variations of the patterned ZnCdSe/ZnCdMgSe QW structures were also probed by micro-PL. The QW emission from a single 50 μm wide stripe was measured at several positions along the stripe width. Figure 3 shows the results from a stripe having emission at 585 nm. The inset shows the positions within the stripe in which the measurements were taken. Identical spectra are observed in the different positions indicating good uniformity of the QW thickness and composition within the patterned region. The spectrum taken exactly at the edge of the stripe (plot No. 4) shows a reduced intensity. However, the peak position is unchanged and no other emission peaks are observed, an indication that no deleterious edge effects are present. Similar results were obtained from the other two regions.

The growth of these three different ZnCdSe/ZnCdMgSe QWs on a single InP substrate illustrates the potential of this material and demonstrates the feasibility of using shadow mask SAE to fabricate integrated full color displays based on the ZnCdMgSe material system. By doping the two barrier layers (one *n* type and one *p* type) and growing a top highly *p*-type doped ZnSeTe contact layer, LEDs could be made from the patterned regions and units such as those shown in Fig. 2 could be fabricated into full color LED display elements and white light sources. Furthermore, since $R-G-B$ lasing has been observed from these materials, integrated full-color display elements based on semiconductor lasers can also be considered. Currently, no other semiconductor materials are available for this application.

In summary, integration of patterned multicolored ZnCdSe/ZnCdMgSe QWs has been performed using shadow mask SAE. Patterned ZnCdSe/ZnCdMgSe QWs with different thickness and Cd compositions, which exhibit excitonic emission in the red, green, and yellow regions, have been grown on a single InP substrate. Excellent optical properties were obtained from the integrated patterned QW regions. These results demonstrate the potential of the (Zn, Cd, Mg)Se material system and the use of shadow mask SAE technique for integrated full-color ($R-G-B$) LED and laser-based display applications.

The authors acknowledge the National Science Foundation through Grant No. ECS-9707213 for support of this research. This work was performed under the auspices of the New York State Center for Advanced Technology (CAT) on Ultrafast Photonic Materials and Applications. The authors also acknowledge support from the Center for Analysis of Structures and Interfaces (CASI) at City College.

[1] K. Koga and T. Yamaguchi, Prog. Cryst. Growth Charact. **23**, 127 (1991).
[2] L. Zeng, B. X. Yang, A. Cavus, W. Lin, Y. Y. Luo, M. C. Tamargo, Y. Guo, and Y. C. Chen, Appl. Phys. Lett. **72**, 3136 (1998).
[3] W. Lin, B. X. Yang, S. P. Guo, A. Elmoumni, F. Fernandez, and M. C. Tamargo, Appl. Phys. Lett. **75**, 2608 (1999).
[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] A. J. Steckl and J. M. Zavada, MRS Bull. **24**, 33 (1999).
[6] A. Y. Cho and F. K. Reinhart, Appl. Phys. Lett. **56**, 2304 (1990).
[7] T. Katsuyama, M. A. Tischler, D. J. Moore, and S. M. Bedair, J. Cryst. Growth **77**, 85 (1986).
[8] H. Saito, I. Ogura, Y. Sugimoto, and K. Kasahara, Appl. Phys. Lett. **66**, 2466 (1995).
[9] Y. Luo, L. Zeng, W. Lin, B. Yang, M. C. Tamargo, Y. M. Strzhemechny, and S. A. Schwarz, J. Electron. Mater. **29**, 598 (2000).
[10] L. Zeng, B. X. Yang, M. C. Tamargo, E. Snoeks, and L. Zhao, Appl. Phys. Lett. **72**, 1317 (1998).
[11] L. Zeng, Ph.D. dissertation, The City College of CUNY, New York, 1998.
[12] A. Cavus, L. Zeng, M. C. Tamargo, N. Bamba, F. Semendy, and A. Gray, Appl. Phys. Lett. **68**, 3446 (1996).