Intersubband Electroluminescence from a ZnCdSe/ZnCdMgSe Quantum Cascade Structure

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Abstract: We show electrically-pumped transverse magnetic polarized intersubband emission from a ZnCdSe/ZnCdMgSe quantum cascade structure grown lattice-matched on InP. Electroluminescence centered near 4.8 µm was observed, in good agreement with calculations.

OCIS codes: (160.6000) Semiconductor materials, (140.5965) Semiconductor lasers, quantum cascade

1. Background

The quantum cascade (QC) laser is an established technology that has broadly enabled new applications at mid-infrared wavelengths, in part because of its substantial wavelength range [1]. The short-wavelength limit of a QC laser is determined by the band offset between the well and barrier materials in the relevant carrier transport band. With a Γ point conduction band offset of 2.1 eV, lasing at 2.95 µm has been achieved from an InAs/AlSb QC structure [2]. However, performance challenges remain for short wavelength III-V QC lasers, due to upper laser state scattering to the indirect valleys of the well material. For example, these valleys limit the "effective" useable band offset for structures containing InAs well material to about 0.75 eV [2].

We have previously proposed achieving larger band offsets [3] via a new material system; based on $Zn_{0.43}Cd_{0.57}Se$ (E_{gap} = 2.08 eV) for QC wells and $Zn_{0.09}Mg_{0.91}Se$ (E_{gap} = 3.59 eV) for the barriers [4], the system has a conduction band offset of 1.2 eV. QC laser design in this material system is furthermore not hindered by the intervalley scattering present in III-V systems, making QC emitters near 1.5 µm possible.

Here, we show first steps toward such a II-VI QC laser, with the development of a ZnCdSe/ZnCdMgSe QC design and corresponding demonstration of first electroluminescence (EL).

2. QC emitter design and fabrication

We present a two-well active region QC structure using $Zn_{0.43}Cd_{0.57}Se$ wells and $Zn_{0.20}Cd_{0.19}Mg_{0.61}Se$ barriers, which are lattice-matched to InP [5].We opted for the quaternary ZnCdMgSe over ZnMgSe, due to present growth challenges associated with using high concentrations of Mg. Figure 1(a) is a conduction band diagram for our structure. The system has a conduction band offset of 780 meV, within which we have designed a 284 meV (4.37 µm) optical transition, labeled *3–>2*. An active region energy state is placed 32 meV below the lower optical transition level (labeled *1*), sufficient for LO phonon depopulation of level *2* via ZnSe (31 meV) and CdSe (27 meV) phonons. The optical dipole matrix element of the *3–>2* transition is calculated to be z_{32} = 8.7 Å, the upper state lifetime τ_3 = 0.84 ps, the lower state lifetime τ_2 = 0.21 ps, and the transition time τ_{32} = 3.3 ps. The emitter was grown by molecular beam epitaxy on an InP:S substrate (doped

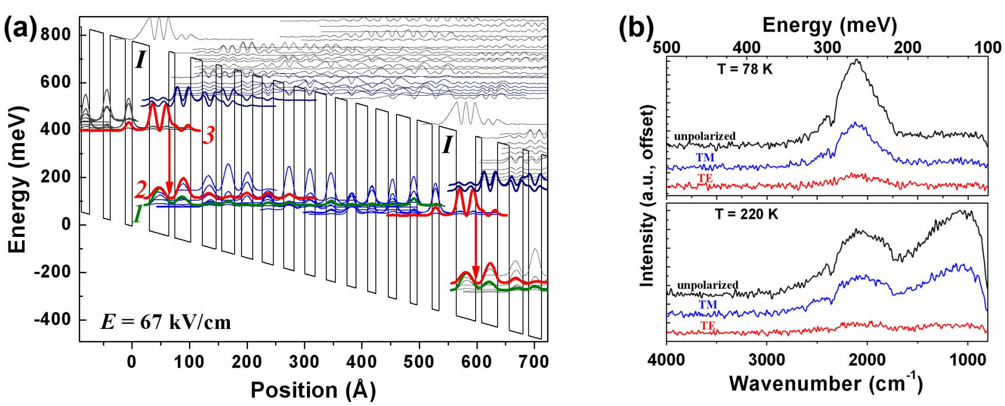

Fig. 1. (a) Conduction band energy diagram, shown under an applied field E = 67 kV/cm. Optical transitions of 284 meV are indicated by arrows. A single stage of the QC layer sequence is (in angstroms starting from the injection barrier ***I***) **30**/34/**10**/28/**20**/24/**10**/22/**12**/20/**16**/20/**18**/18/**18**/18/**20**/16/**20**/**20**/14/**22**/14/**24**/12/**26**/12, where ZnCdMgSe barriers are in bold and ZnCdSe wells are in normal font. Underlined layers represent ZnCdSe that is Cl-doped (2×10^{17} cm^{-3}) and ZnCdMgSe doped with the same $ZnCl_2$ flux as the ZnCdSe layers. (b) Polarization-dependent emission spectra for a device driven with 3.6 A and 3% duty cycle at 78 K and 220 K. The emission is predominantly TM polarized.

n < 2×10^{17} cm^{-3}). Active core growth was preceded by a 0.25 µm $In_{0.53}Ga_{0.47}As$ (Si doped 5×10^{17} cm^{-3}) buffer layer, a 40 sec Zn flux treatment, and a 410 Å $Zn_{0.43}Cd_{0.47}Se$ (Cl doped 2×10^{17} cm^{-3}) buffer layer. Following 10 periods of active region-injector growth, 400 Å ZnCdSe (Cl doped 2×10^{17} cm^{-3}) and 2000 Å ZnCdSe (Cl doped 8×10^{18} cm^{-3}) cap layers were grown. Digital transition gradings were used between bulk layers and the active core.

Electroluminescence structures in the form of circular mesas of 400 µm diameter were lithographically patterned and etched with $HBr:HNO_3:H_2O$ (1:1:10). An O_2 plasma cleaning followed by a 45 sec $HF:H_2O$ (1:1) dip immediately preceded top contact metal deposition. Top contacts consisted of 150 Å Ti followed by 2500 Å Au; Ge/Au back-side InP contacts were also deposited. Finally, the mesas were cleaved into semicircular EL structures, In soldered to Cu heat sinks, and the top electrical contacts wire bonded to submounts.

3. Device testing and analysis

Electroluminescence was collected for a variety of temperatures and currents using a Fourier transform infrared (FTIR) spectrometer and a cooled HgCdTe detector. Intersubband optical transitions in quantum wells are TM-polarized because an optical dipole matrix element only exists for photon fields parallel to the growth (i.e. quantization) direction. The spectra were found to be predominantly TM-polarized, as shown in Fig. 1(b), for a range of temperatures. Figure 2(a) shows low-temperature pulsed emission spectra for pumping currents ranging from 1.0 to 3.6 A. Electroluminescence is centered near 2100 cm^{-1} (4.8 µm). Full-width at half-maxima (FWHM) are ~400 cm^{-1}, which may result from a combination of interface roughness broadening and electron transitions between multiple energy levels. The temperature dependence of the EL is shown in Fig. 2(b), all spectra being taken for a current of 2 A. In addition to the primary 2100 cm^{-1} peak, secondary lower-energy emission develops with increasing temperature, the origin of which is still under investigation. Figure 2(c) shows light-current-voltage measurements for temperatures ranging from 78 to 220 K. Voltage turn-on for 78 K occurs at 5.4 V. Attributing 3.3 V to the drop over the QC stack and another 0.35 V to other material interfaces, the remaining 1.75 V is dropped over the contacts.

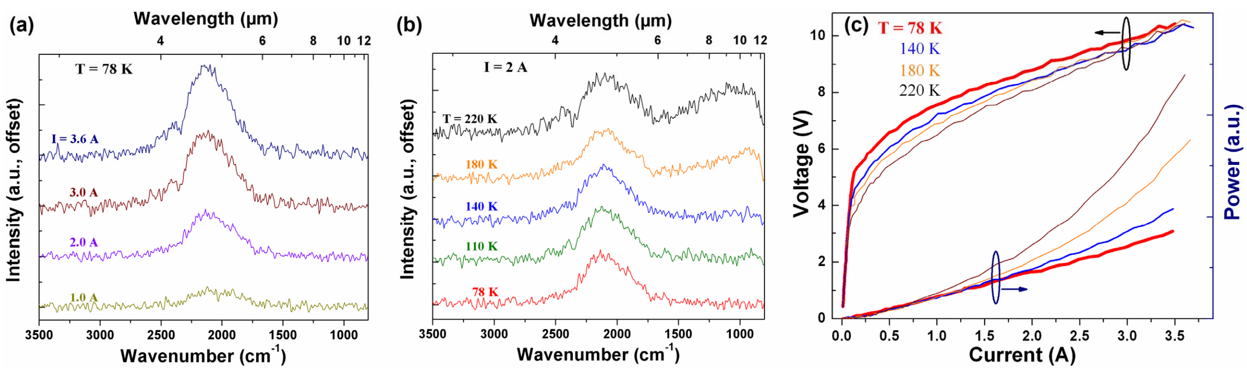

Fig. 2. (a) Electroluminescence (EL) spectra for variations in current at T = 78 K. Peak emission is centered near 4.8µm. (b) EL spectra at I = 2 A for temperatures from 78 to 220 K. Additional longer-wavelength light is seen with increasing temperature. (c) Light-current-voltage data from 78 to 220 K. All measurements were taken for a device driven by 1 µs pulses at 3% duty cycle.

4. Conclusions

We have demonstrated the first ZnCdSe/ZnCdMgSe QC structure from which intersubband EL has been observed. The TM-polarized emission is centered near 4.8 µm, in good agreement with calculations. Longer-wavelength thermally induced emission is also observed.

5. Acknowledgements

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6. References

[1] C. Gmachl, F. Capasso, D. L. Sivco, and A. Y. Cho, "Recent progress in quantum cascade lasers and applications," *Rep. Prog. Phys.*, **64**, 1533 (2001).

[2] J. Devenson, R. Teissier, O. Cathabard, and A. N. Baranova, "InAs/AlSb quantum cascade lasers emitting below 3 mu m," *Appl. Phys. Lett.*, **90**, 111118 (2007).

[3] M. Munoz, H. Lu, X. C. Zhou, M. C. Tamargo, and F. H. Pollak, "Band offset determination of Zn0.53Cd0.47Se/Zn0.29Cd0.24Mg0.47Se," *Appl. Phys. Lett.*, **83**, 1995 (2003).

[4] M. Sohel, M. Munoz, and M. C. Tamargo, "Molecular beam epitaxial growth and characterization of zinc-blende ZnMgSe on InP (001)," *Appl. Phys. Lett.*, **85**, 2794 (2004).

[5] W. O. Charles, A. Shen, K. J. Franz, C. Gmachl, Q. Zhang, Y. Gong, G. F. Neumark, and M. C. Tamargo, "Growth and Characterization of ZnxCd1-xSe/Znx'Cdy'Mg1-x'-y'Se Asymmetric Coupled Quantum Well Structures for Quantum Cascade Laser Applications," *Proceedings of the North American Conference on Molecular Beam Epitaxy, Sept. 2007,* in *J. Vac Sci. Tech B* (2008).