

ZnCdSe/ZnCdMgSe Quantum Cascade Electroluminescence

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Abstract

This letter reports electroluminescence emission from a ZnCdSe/ZnCdMgSe quantum cascade (QC) structure. With a two-well QC active region design, the II-VI heterostructure was grown lattice-matched on an InP substrate by molecular beam epitaxy. Deep etched mesas were electrically pumped at current densities up to 10 kA/cm², producing optical emission centered near 4.8 μ m, in good agreement with the structure design. The light is predominantly TM polarized, confirming its intersubband origin. Electroluminescence was observed from 78 to 300 K.

Key words:

ZnCdSe, ZnCdMgSe, quantum cascade, electroluminescence, intersubband, II-VI, heterostructure

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78.60.Fi Electroluminescence

85.35.Be Quantum wells: devices

81.05.Dz Fabrication of II-VI semiconductors

Quantum cascade (QC) development has enabled robust generation of mid-infrared light. To date, the workhorse material for mid-infrared QC lasers has been the InGaAs/AlInAs material system¹; lasers from this material have reached the technological benchmark of room temperature, continuous wave operation.² However, performance is not as advanced at wavelengths below 4 μm . Such high energy photon generation in QC structures is fundamentally limited by the band offset between the well and barrier materials in the relevant carrier transport band. In addressing this fundamental limit, Sb-based III-V heterostructures have demonstrated the shortest wavelength operation to-date achieved for any QC laser: 2.75 μm .³ Sb-based materials are appealing for short-wavelength QC lasers because of their large Γ valley conduction band-offsets—in InAs/AlSb up to 2.1 eV.⁴ In this material system, however, scattering out of the upper laser energy state into satellite valleys limits the “effective” usable band offset to ~ 0.75 eV.⁴

Materials systems other than III-V antimonides have been proposed to address the challenges of shorter-wavelength photon generation through intersubband transitions. GaN/AlGaIn QC structures have shown intersubband photoluminescence at $\lambda \approx 2.13$ μm ,⁵ and GaN/AlGaIn QC photodetectors have been demonstrated with responsivity near $\lambda \approx 1.7$ μm .⁶ Electroluminescence from CdF₂/CaF₂ QC structures grown on Si has also been reported.⁷

We have previously proposed the Zn_{0.43}Cd_{0.47}Se/Zn_{0.09}Mg_{0.91}Se system grown lattice-matched on InP as a large band offset QC emitter alternative.^{8,9} The ZnCdSe/ZnMgSe system has a Γ valley band offset of 1.2 eV (Ref. 8); all of it is usable for QC laser design due to the absence of satellite valleys.¹⁰ Such design space makes

ZnCdSe/ZnMgSe QC emitters possible near 1.5 μm . Alternately, because of magnesium's susceptibility to oxidation, the $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{Se}/\text{Zn}_{0.20}\text{Cd}_{0.19}\text{Mg}_{0.61}\text{Se}$ variant is currently more technologically practicable.⁹ Here, we demonstrate initial steps toward a II-VI QC laser, with the development of a ZnCdSe/ZnCdMgSe QC structure that exhibits intersubband electroluminescence.

We have developed a conventional two well active region QC structure in the $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{Se}/\text{Zn}_{0.20}\text{Cd}_{0.19}\text{Mg}_{0.61}\text{Se}$ material system. The Fig. 1 conduction band diagram shows the structure for an applied field of 67 kV/cm; a single stage of the layer sequence is—in angstroms starting from the injection barrier *I*, and going from left to right in the direction of electron flow—

30/34/10/28/20/24/10/22/12/20/16/20/18/18/18/18/20/16/20/16/20/14/22/14/24/12/26/12.

ZnCdMgSe barriers are in bold and ZnCdSe wells are in normal font. Underlined layers represent ZnCdSe that is Cl-doped ($2 \times 10^{17} \text{ cm}^{-3}$) and ZnCdMgSe doped with the same ZnCl_2 flux as the ZnCdSe layers. We estimate a sheet density per active region-injector period of $n_{2D} = 5.4 \times 10^{11} \text{ cm}^{-2}$. We designed an optical transition of 284 meV (4.37 μm) with a calculated optical dipole matrix element $z_{32} = 8.7 \text{ \AA}$. An active region energy state is placed 32 meV below the lower optical transition level, sufficient for longitudinal optical (LO) phonon depopulation of the lower laser state via ZnSe- (31.6 meV) (Ref. 11) and CdSe-like (26.3 meV) (Ref. 12) phonons. This configuration results in a calculated upper state lifetime $\tau_3 = 0.84 \text{ ps}$, lower state lifetime $\tau_2 = 0.21 \text{ ps}$, and non-radiative transition time $\tau_{32} = 3.3 \text{ ps}$. We considered band gaps of 2.08 and 3.03 eV for $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{Se}$ and $\text{Zn}_{0.20}\text{Cd}_{0.19}\text{Mg}_{0.61}\text{Se}$, respectively, with a conduction band offset of

0.78 eV (Ref. 13). The corresponding conduction band effective masses are calculated to be 0.128 and 0.181 (Ref. 13) times the free electron mass, respectively.

The QC emitter was grown by molecular beam epitaxy on a low doped ($n < 2 \times 10^{17} \text{ cm}^{-3}$) InP:S substrate.¹⁴ Prior to active core growth, we deposited 0.25 μm of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (Si doped $5 \times 10^{17} \text{ cm}^{-3}$) as buffer layer. II-VI growth was preceded by a 40 sec Zn flux treatment and 100 Å of low temperature (230 °C) ZnCdSe (Cl doped $2 \times 10^{17} \text{ cm}^{-3}$). At the 330 °C growth temperature, another 400 Å of ZnCdSe (Cl doped $2 \times 10^{17} \text{ cm}^{-3}$) buffer was deposited. Ten periods of the active region-injector sequence were grown. The structure was capped by 400 Å ZnCdSe (Cl doped $2 \times 10^{17} \text{ cm}^{-3}$) and 2000 Å ZnCdSe (Cl doped $4 \times 10^{18} \text{ cm}^{-3}$). Digital transition gradings were used between bulk layers and the active core.

Polarization-dependent multi-pass transmission measurements were performed using a Fourier transform infrared (FTIR) spectrometer on a sample with each end polished to 45°. Two dominant transverse magnetic (TM) absorption peaks were observed, shown in Fig. 2, within which we were able to fit three Gaussian curves. Calculations for zero field energy transitions are indicated in Fig. 2 and are consistent with the observed absorption.

Electroluminescence (EL) structures were fabricated in the form of semicircular cleaved mesas. Lithographically patterned 400 μm diameter circles were etched into mesa structures using a $\text{HBr}:\text{HNO}_3:\text{H}_2\text{O}$ (1:1:10) wet chemical etch solution; the etch depth was sufficient to penetrate the epitaxially grown material. A second lithography step was used to apply the top contact metallization. An O_2 plasma cleaning followed by a 45 sec $\text{HF}:\text{H}_2\text{O}$ (1:1) dip immediately preceded top metal contact 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 and In soldered to Cu heat sinks; the top electrical contacts were wire bonded to contact pads. Cleaved mesa areas were measured as around 0.036 mm².

Electroluminescence was collected for a variety of heat sink temperatures and applied current values using an FTIR spectrometer in step scan mode and a cooled HgCdTe detector. The applied current pulses were 1 μs in duration at 3% duty cycle.

We observed EL centered near $\lambda \approx 4.8$ μm. Emission polarization characteristics were examined to confirm intersubband light generation; intersubband optical transitions in quantum wells are TM polarized. Two exemplary results of polarization-resolved EL spectra are shown in Fig. 3 for heat sink temperatures of 78 K and 220 K and a pumping current of 9.6 kA/cm². While a small amount of transverse electric (TE) light is observed, which we attribute to scattering from within the rounded mesa, the EL is predominantly TM polarized.

At low temperatures, the primary emission peak is observed near 4.8 μm. Figure 4 shows emission behavior with increasing current for a heat sink temperature of 78 K and no polarizer in the optical path. The 4.8 μm emission peak grows correspondingly with increasing pumping current. At a pumping current density of 2.8 kA/cm², a Gaussian fit gives the EL full-width at half-maximum (FWHM) as 52 meV; at 9.6 kA/cm² the FWHM is 47 meV, which is about 20% of the transition energy.

This 4.8 μm light is seen at temperatures ranging from 78 K to 300 K. Figure 5 shows spectra with increasing temperature for a pumping current density of 9.6 kA/cm². All spectra represent TM polarized light with subtraction of the corresponding

unpolarized background. The emission peak centered near 4.8 μm is present over the full temperature range. We also observed the growth of a secondary, temperature-induced, lower energy emission. This broad emission is more intense for both higher currents and higher temperatures. Accounting for the longer wavelength emission, the relative intensity of the 4.8 μm peak decreases with increasing temperature. Reported spectra are not corrected for wavelength-dependent variations in detector responsivity; we estimate our detector is 55% more sensitive for 120 meV photons than for 260 meV photons. While the origin of this low energy emission is still under investigation, the 4.8 μm intersubband emission is dominant and persists through room temperature.

Figure 6 shows wavelength-integrated light-current-voltage (LIV) measurements for temperatures ranging from 78 to 300 K. The light-current (LI) data represent TM polarized emission. The observed output power grows superlinearly for both increasing current and increasing temperatures. The current-voltage (IV) curves show typical QC behavior, with characteristic current turn-on once sufficient voltage has been applied. Turn-on for 78 K occurs at 5.40 V. At a turn-on field of 64 kV/cm, 3.42 V is dropped over the active core. We attribute to conduction band offsets at bulk interfaces another 0.35 V. The remaining 1.63 V is likely dropped over the as yet non-ideal top contacts.

In conclusion, we have designed, grown, and tested a ZnCdSe/ZnCdMgSe QC structure exhibiting room temperature EL. The II-VI intersubband emitter has primarily TM polarized emission centered near 4.8 μm in good agreement with the as-designed structure.

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Fig. 1. (Color online) A portion of the conduction band energy diagram under an applied field of 67 kV/cm. $\text{Zn}_{0.43}\text{Cd}_{0.57}\text{Se}$ wells and $\text{Zn}_{0.20}\text{Cd}_{0.19}\text{Mg}_{0.61}\text{Se}$ barriers are used to create a 284 meV optical transition, represented by wavy arrows. The injection barrier is signified by I .

Fig. 2. (Color online) Transverse magnetic absorption spectrum from multipass transmission analysis. Fitted Gaussians show three resolvable peaks. Optical transition calculations for zero applied field are indicated at the top. The inset shows the multipass configuration with broadband light passing through a sample polished to 45° on both ends.

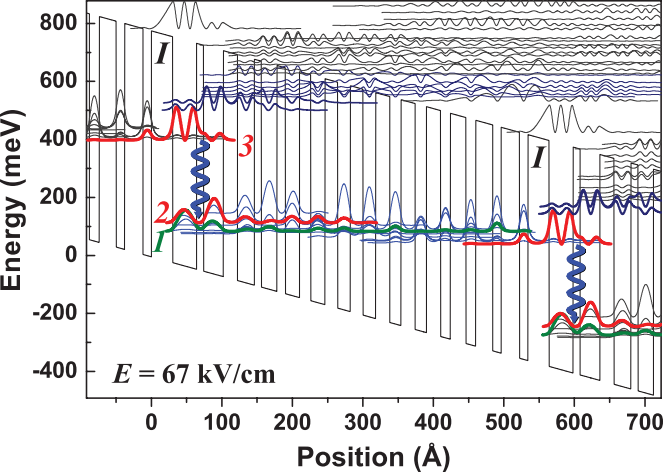
Fig. 3. (Color online) Polarization-resolved EL spectra for a device driven with 9.6 kA/cm² at 78 K (top) and 220 K (bottom). The emission is predominantly TM polarized. Additional longer wavelength light is seen at higher heat sink temperatures and currents. Atmospheric CO₂ absorption can be seen near $\lambda \approx 4.2 \mu\text{m}$. Spectra are not corrected for detector responsivity, which is more sensitive at longer wavelengths.

Fig. 4. (Color online) Electroluminescence spectra at $T = 78 \text{ K}$ and various current levels as indicated. Emission is centered near 4.8 μm .

Fig. 5. (Color online) Electroluminescence spectra at 9.6 kA/cm² for heat sink temperatures from 78 to 300 K. Additional longer-wavelength light is seen with increasing temperature. Subtraction of the low energy emission shows that the intensity

of the 4.8 μm EL decreases with increasing temperature. Spectra are not corrected for variations in detector responsivity, which is more sensitive at longer wavelengths.

Figure 6. (Color online) Spectrally integrated light-current-voltage data from 78 to 300 K. The data were collected with 1 μs pulses at 3% duty cycle. Data are not corrected for detector responsivity.



TM Absorption (a.u.)

