Intersubband transitions in molecular-beam-epitaxy-grown wide band gap II-VI semiconductors

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The authors report the study of intersubband transitions in ZnCdMgSe-based wide band gap II-VI semiconductors. The samples were prepared by molecular beam epitaxy on InP substrates. Both ZnCdSe/ZnCdMgSe multiple quantum wells and CdSe/ZnCdMgSe quantum dot multilayer stacks were grown. Strong intersubband absorption was observed in the samples. The results show that these materials are very promising for fabricating intersubband devices in the mid- and near-infrared spectral ranges. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2720859]

I. INTRODUCTION

Wide band gap II-VI semiconductors are very promising materials for fabricating various optoelectronic devices due to their excellent optical properties.[1] ZnCdMgSe grown lattice matched to InP substrate is an interesting material system with an adjustable band gap that can be continuously tuned from 2.1 to 3.6 eV.[2,3] ZnCdMgSe-based heterostructures have been shown to have interband luminescence emissions covering the entire visible wavelength range, opening up promising potential applications. Here we report the study of intersubband (ISB) transitions in the material system for exploring its suitability for ISB devices.

The development of ISB devices,[4] such as quantum cascade lasers and quantum-well infrared photodetectors, is one of the most successful stories in engineering quantum potentials for practical device application. The realization of these devices has been made possible by the convergence of molecular beam epitaxy[5] (MBE) and band structure engineering.[6] Intersubband devices are unipolar devices, eliminating the need for *p*-type doping, which has been shown to be difficult in wide band gap II-VI materials. The large conduction band offset[7] in the material system offers advantages over traditional III-V's such as to realize intersubband devices operating at shorter wavelengths and at higher temperature. In this article, we present the results on ISB absorption in MBE-grown ZnCdSe/ZnCdMgSe multiple quantum wells (MQWs) and CdSe/ZnCdMgSe self-assembled quantum dot (QD) multilayer stacks.

II. MBE GROWTH

The samples were grown by MBE on (001) semi-insulating InP in a dual-chamber Riber 2300P system. After the removal of oxide layer under As flux and the growth of a 0.15 μm InGaAs buffer layer in the III-V growth chamber, the samples were transferred through vacuum modules to the II-VI growth chamber. There the InGaAs surface was exposed to a Zn flux for 10 s followed by the growth of a 10 nm low-temperature ZnCdSe buffer layer at 200 °C. The substrate temperature was then raised to 300 °C to grow the subsequent layers. To ensure the lattice matching of both the ZnCdSe and the ZnCdMgSe to the InP substrate two Zn cells were employed. Three ZnCdSe/ZnCdMgSe MQW samples (denoted W1, W2, and W3) and three CdSe/ZnCdMgSe QDs multilayer samples (denoted D1, D2, and D3) were grown.

The three MQW samples consist of 60 (W1), 80 (W2), and 100 (W3) repeats of ZnCdSe/ZnCdMgSe QWs. The ZnCdSe well thicknesses are 42, 28, and 22 Å for samples W1, W2, and W3, respectively. The well was doped with Cl (using $ZnCl_2$ as dopant source) to 2×10^{18} cm^{-3}. The ZnCdMgSe barrier thickness was about 100 Å. The band gap of the barrier in samples W1 and W2 is 2.9 eV and that for sample W3 is 2.8 eV at room temperature (RT).

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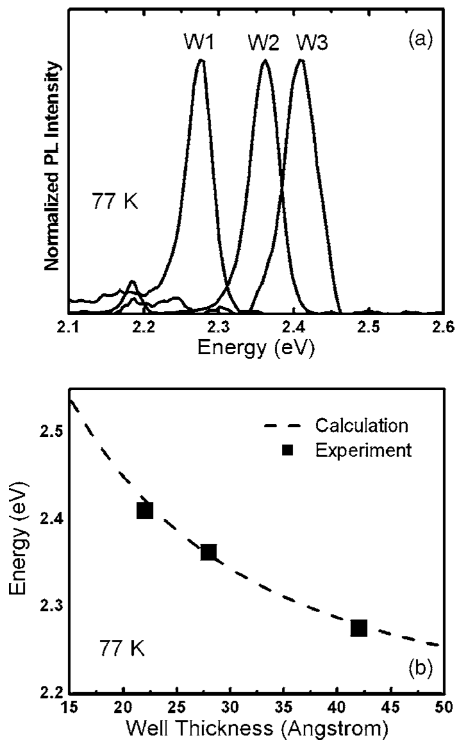

FIG. 1. (a) 77 K PL spectra of the three MQW samples with different QW widths. (b) PL emission energy as a function of well thickness. The dashed line is the theoretical value obtained with an envelope function approximation calculation.

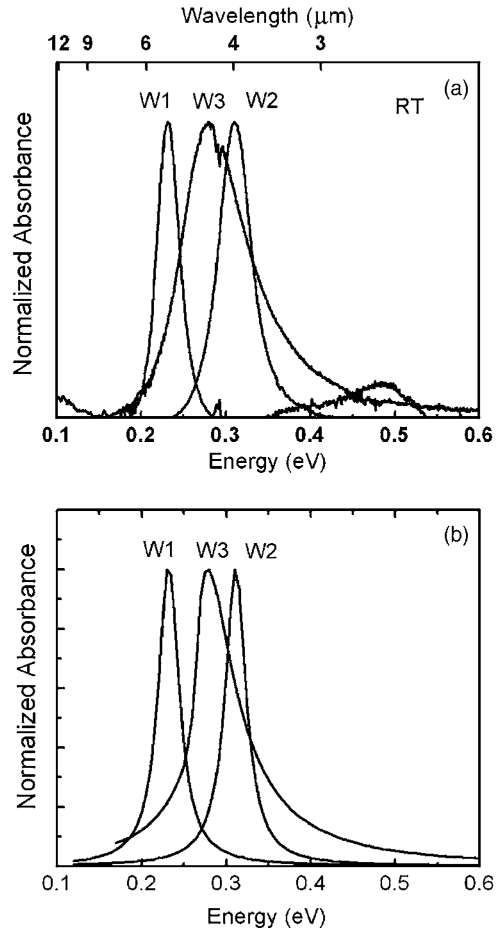

FIG. 2. (a) Normalized absorbance of the three MQW samples measured by FTIR at RT. (b) Calculated line profiles for the three samples using the analytical expression in Ref. 10.

The three QD samples consist of 50 repeats of CdSe/ZnCdMgSe. The ZnCdMgSe barrier layer thickness in these samples is 18 nm. The band gap of the barrier is about 2.9 eV at RT. Samples D1 and D2 have identical structures except that sample D1 is undoped while in sample D2 the CdSe QD layers were doped with Cl. The nominal CdSe thickness deposited for samples D1 and D2 is 1.56 nm, and corresponds to 5.2 ML. For sample D3, the CdSe QD layers with a nominal deposited thickness of 6.9 ML were also doped with Cl. The two-dimensional carrier densities in samples D2 and D3 are about 3×10^{11} and 4×10^{11} cm^{-2}, respectively.

III. ZnCdSe/ZnCdMgSe MQWs

Figure 1(a) shows the photoluminescence (PL) spectra of the three MQW samples at 77 K. PL measurements were performed at RT and liquid-nitrogen (77 K) temperature by using the 325 nm line of a He–Cd laser as an excitation source. A 0.22 m SPEX 1680-B double grating spectrometer connected to a photomultiplier was used for detection. Sharp peaks from the MQWs can be seen from the samples with no traces of deep level emissions. The emission energy as a function of well thickness is plotted in Fig. 1(b). The dashed line is the theoretical value obtained with an envelope function approximation calculation. Since the interband transition energy is not very sensitive to the barrier height, we neglected the difference in barrier heights between sample W3 and that of samples W1 and W2 and used the 2.9 eV as the band gap of the barrier layer. A conduction band discontinuity of 80% of the total band gap difference is used.[8]

For ISB absorption measurements, samples were fabricated to the waveguide geometry with parallel 45° facets. The absorption measurements were performed at RT using a Bomem MB-100 Fourier transform infrared (FTIR) spectrometer. A cooled HgCdTe detector was used. Figure 2(a) shows the normalized absorbance of the three samples. The spectra were obtained by taking the ratio of *p*-polarized spectra over *s*-polarized spectra. As expected, the ISB transition energy increases (from 0.23 eV for sample W1 to 0.31 eV for sample W2) with the decrease of well thickness as it changes from 42 Å (in W1) to 28 Å (in W2). The absorbance peak of samples W1 and W2 is narrow ($\Delta\lambda/\lambda$ is of the order of 10%) and symmetric, a signature of bound-to-bound transition, as usually observed in conventional III-V semiconductors.[4] When the well thickness is further decreased to 22 Å (in W3), instead of moving further to higher energy, the absorption peak moved back to a lower energy (0.28 eV), in between samples W1 and W2. Furthermore, the absorbance of sample W3 is broad ($\Delta\lambda/\lambda\sim30\%$) and asymmetric, typical of bound-to-continuum transitions in QWs. Although bound-to-continuum transitions are frequently used

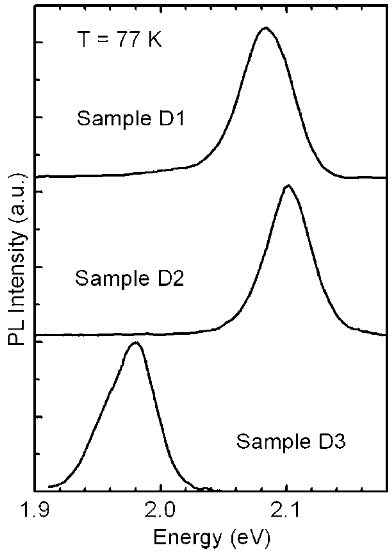

FIG. 3. PL spectra of three QD multilayer samples measured at 77 K.

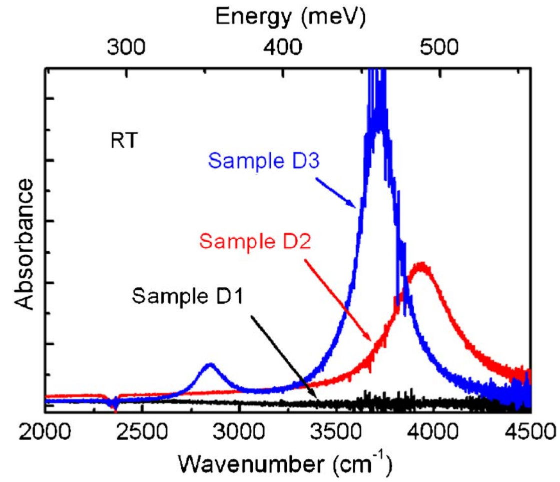

FIG. 4. Absorbance of three QD samples measured by FTIR at RT.

in quantum-well infrared photodetectors,[9] to fabricate devices operating at shorter wavelength we need to increase the barrier height in the MQWs. Figure 2(b) is the calculated absorbance of the three samples obtained by using the analytical expression derived by Liu.[10] A broadening factor of 15 meV was used for samples W1 and W2 and 30 meV was used for W3. For simplicity, the tangent term in Liu's formula is taken as 1. The asymmetrical nature of the bound-to-continuum transition is very obvious.

IV. CdSe/ZnCdMgSe QD MULTILAYERED STRUCTURES

Figure 3 shows the PL spectra for the three QD samples measured at 77 K. Comparing sample D3 to samples D1 and D2, the emission energy of D3 shifts to lower energy as a result of increased dot size, which is consistent with our previous observation.[11] Although samples D1 and D2 were grown under the same growth condition with the same structure, except the doping, the emission energy of sample D2 is slightly higher than that of sample D1. This could be due to the fact that the presence of Cl in the CdSe may slightly affect the dot size.

Intersubband absorption measurements were performed using a Nicolet Nexus-870 FTIR spectrometer equipped with a liquid-nitrogen-cooled HgCdTe detector. Samples were also fabricated to the waveguide geometry with parallel 45° facets. Figure 4 shows the absorbance of the three samples at room temperature. The spectra were obtained by taking the ratio of *p*-polarized spectra over *s*-polarized spectra. For sample D1, which is undoped, no absorption features were observed. An absorption with a peak at 2.54 μm (0.49 eV) was observed for sample D2. Lorentzian line fitting of the absorbance spectrum yields a full width at half maximum (FWHM) of 46 meV. The narrow linewidth ($\Delta\lambda/\lambda_p \sim 9.4\%$) is an indication of relatively uniform distribution of dot size. For sample D3, two absorption peaks were observed at 2.69 μm (0.46 eV) with a FWHM of 29 meV ($\Delta\lambda/\lambda_p \sim 6.3\%$) and at 3.51 μm (0.35 eV) with a FWHM of 20 meV ($\Delta\lambda/\lambda_p \sim 5.7\%$). We believe that the peak at 0.35 eV originates from the transition between the ground and the first excited states in the QDs. The original of the second peak at 0.46 eV is not understood at present. Further experiments, such as temperature-dependent ISB absorption measurements and photoresponse (photocurrent) measurements, may help us better understand the origin of that second peak.

We note that the ISB absorption in our QD samples is polarization dependent. Similar results have been reported for Ge (Ref. 12) and GaN/AlN (Ref. 13) QD systems. The common feature of these QDs is that the lateral (base) size is much larger than the height. This makes the quantum confinement mainly happens in the vertical (growth) direction. Even if there were confinement in the lateral direction, the ISB absorption arising from the confinement would appear in the much longer wavelength range. Aslan *et al.*[14] have reported that in InAs/GaAs QDs the ISB absorption is dominated by *p* polarization in the midinfrared region, while the *s*-polarized response appears at longer wavelength. This issue has also been theoretically addressed by Zhang and Galbraith.[15]

V. SUMMARY

In summary, we have grown by MBE and studied properties of MQWs and QD multilayer structures using the ZnCdMgSe-based wide band gap II-VI semiconductors. Strong intersubband absorption is observed in these materials, showing the potential of fabricating intersubband devices with them, especially for short wavelength applications.

ACKNOWLEDGMENTS

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