MBE
Room Silver Creek - Session MBE-2WeM
Heterostructures and Quantum Dots

Moderator: Stephanie Law, University of Delaware

10:30am **MBE-2WeM10 Vertical Hole Transport in InAs/InAs$_{1-x}$Sb$_x$ Type-II Superlattices**, ***Cheng-Ying Tsai***, *Y. Zhang, Z. Ju, Y.-H. Zhang,* Arizona State University

This abstract reports the study of the vertical hole transport in InAs/InAs Sb strained layer type-II superlattice . The low hole mobility in InAs/InAs$_{1-x}$Sb$_x$ superlattice is considered as the main reason for the low internal quantum efficiency of its mid-wave and long-wave infrared photodetectors, compared with that of its HgCdTe counterparts. Optical measurements using time-resolved photoluminescence (TRPL) and steady-state photoluminescence (SSPL) are implemented to extract the diffusion coefficients and mobilities of holes in the superlattices at various temperatures.

The structure of the samples consists of a mid-wave infrared superlattice (MWSL) absorber region grown atop a long-wave infrared superlattice (LWSL) probe region by using MBE. When the sample is illuminated by laser light, the photogenerated carriers in the MWSL region will diffuse into the LWSL probe region and give photoluminescence, which is used to measure the time of flight of the holes that vertically transport through the entire MWSL region. The hole diffusion coefficients and mobilities in the MWSL can be determined by fitting the TRPL decay profile with the diffusion and rate equations, or by the ratio of the integrated SSPL intensities from LWSL and MWSL.

The carrier dynamics in LWSL and MWSL can be described by rate equation and diffusion equation, assuming no external electric field, respectively. The diffusion in the LWSL is negligible due to its thin thickness compared with that of MWSL. The extracted mobilities from SSPL at various temperatures are illustrated in Figure 1, which shows a hole mobility of 56 cm^2/Vs at 70 K. Besides, the extracted mobility from TRPL fitting (Figure 2) gives a hole mobility of 54 cm^2/Vs at 70 K, which is in excellent agreement with the result measured by using SSPL.

10:45am **MBE-2WeM11 Room Temperature THz Intersubband Transitions in Continuously-graded Al$_x$Ga$_{1-x}$As Parabolic Quantum Well Arrays**, *C. Deimert,* University of Waterloo, Canada*; P. Goulain, J.-M. Manceau, A. Bousseksou,* CNRS and University of Paris-Sud, France*; W. Pasek, T. Yoon, N.Y. Kim,* University of Waterloo, Canada*; R. Colombelli,* CNRS and University of Paris-Sud, France*;* ***Zbigniew Roman Wasilewski***, University of Waterloo, Canada

While conventional THz optoelectronic devices operate in the weak coupling regime between light and matter, the strong coupling regime provides an attractive alternative. For such devices, parabolic quantum wells (PQWs) will be critical in enabling operation up to room temperature. Unlike the more ubiquitous square wells, PQWs have equal intersubband (ISB) spacing, which provides a strong, unified absorption line independent of thermal occupation.

PQWs in Al$_x$Ga$_{1-x}$As can be grown with molecular beam epitaxy (MBE) using digital alloys, however this technique only approximates the parabolic potential, and it also generates many interfaces. We instead generate a smooth composition gradient, employing a linear dynamical model of our Al cell to smoothly vary the flux at standard growth rates [1].

Using this technique, we grow a stack of 54 PQWs with Al varying between 2-30%. We demonstrate the quality of this sample using multipass transmission spectroscopy. The measured transmittance in Figure 1 demonstrates a clear THz ISB absorption at both 300K and 8K with minimal shift of the peak. The temperature dependence of the linewidth is particularly noteworthy – below 100K, the linewidth is exceptionally small, reaching a record-low value of 5.7% of the center frequency.

Further work will aim at incorporating these PQW arrays into THz devices operating in the strong coupling regime at around 100K, obtaining performance levels presently only achievable at liquid helium temperature.

[1] C. Deimert, Z. R. Wasilewski, *Journal of Crystal Growth* **514**, 103-108 (2019).

11:00am **MBE-2WeM12 Excitonic Properties of Asymmetric Triple CdSe Quantum Wells**, *F. Hernández-García,* Cinvestav-IPN, México*; F. Sutara,* ***Isaac Hernández-Calderón***, CINVESTAV, México

Asymmetric triple quantum wells (ATQWs) present interesting optical properties that can be modulated as a function of the separating barriers thicknesses. The number of excitonic transitions and their energies will depend on the degree of overlap of the exciton wave functions in the quantum wells. If the barriers are thick enough, we will observe three fundamental optical transitions, one for each (single) QW. If the barriers are very thin, which allow strong quantum well coupling, the ATQW will present only one fundamental transition because the three QWs constitute a *single quantum system*. ATQWs with barrier thicknesses within those extremes can present two or three emission peaks with energies and intensities depending on the thickness of each separating barrier. A previous study on asymmetric double ultra-thin quantum wells of CdSe within ZnSe barriers demonstrated that the thinner QWs required several tens of nm to decouple the QWs and that ZnSe barriers of around 5 nm caused a strong coupling of the ultra-thin CdSe QWs [1].

Here, we present the results of the epitaxial growth and the low temperature photoluminescence characterization of the excitonic emission of three different ATQW heterostructures, two made with thin ZnSe barriers of 5 nm that produce strong coupling, and one heterostructure with thick 100 nm ZnSe barriers. Each heterostructure contains three CdSe QWs, with thicknesses of 1, 2 and 3 MLs. In the coupled heterostructures the QWs were grown in two sequences 1-2-3 and 3-2-1; the uncoupled heterostructure was grown with the sequence 3-2-1; the first QW is always closer to the GaAs(001) substrate. The QWs were grown by atomic layer epitaxy within ZnSe barriers grown by molecular beam epitaxy, all samples were grown at 275 °C. For the coupled ATQW heterostructures we observed only one optical transition around 2.34 eV, for the uncoupled ATQW we observed three excitonic peaks around 2.32, 2.48 and 2.67 eV, as expected. The electronic structure of each ATQW system as well as the peculiarities of their excitonic spectra will be explained in terms of the structural properties of the heterostructures and the degree of coupling of the QWs.

[1] J. A. Lorenzo-Andrade, F. Sutara, I. Hernández-Calderón, Superlattices and Microstructures 87, **47** (2015).

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11:15am **MBE-2WeM13 Gain Measurements of Se-based II-VI Multiple Quantum Well Structures for Vertical-External-Cavity Surface-Emitting Laser Applications**, *K. Zhao,* The City College of New York*; G. Chappell, J. Hastie,* University of Strathclyde, UK*; S.K. Gayen,* The City College of New York/Graduate Center of CUNY*;* ***Maria Tamargo***, City College of New York, City University of New York

Vertical-external-cavity surface-emitting lasers (VECSELs), also known as semiconductors disk lasers (SDLs), have captured the interest of many researchers due to their unique features, such as high output power, ultrashort pulse operation, thin gain region, and wide spectral coverage. VECSELs based primarily on III-V quantum wells structures have been well developed. However, it is still challenging to achieve devices working in the yellow and green wavelengths. Se-based II-VI materials such as ZnCdSe and ZnCdMgSe grown lattice matched to InP are attractive materials for this application. Recently our groups have reported some initial results pertaining to the optically pumped lasing potential of these materials. However, optimizing the materials for the very stringent structural requirements of the VECSEL requires a better understanding of the optical properties of the Se-based II-VI materials.

We report on the growth by molecular beam epitaxy of multiple quantum well (MQW) ZnCdSe/ZnCdMgSe structures for application as VECSELs devices operating at 565 nm. X-ray diffraction (XRD) 2θ-ω scan obtained along the (002) reflection, with clear evidence of thickness fringes, confirms the excellent crystalline quality of the samples. The structures were characterized using a pump probe technique from which the optical gain of the material could be estimated. For these measurements it was necessary to remove the absorbing InP substrate by a selective chemical etching technique. Gain values of ~9% were obtained for near-lattice matched samples. We will present results of the effect on gain of structural parameters, such as strain. The results will inform the design of the optimum VECSEL structure.

11:30am **MBE-2WeM14 Structural and Optical Properties of PbTe/CdTe/InSb Heterostructures Grown using Molecular Beam Epitaxy***,* ***Tyler McCarthy****,* Arizona State University

Rock-salt lead chalcogenides are of much current interest for several reasons, including their direct band gap in the infrared (IR) wavelength range [1]. Integrating II-VI and IV-VI chalcogenides with III-V compounds into epitaxial heterostructures combines the advantages of wide-band gap II-VI binaries and alloys, good for electrical and optical confinement, with narrow-band gap III-V and IV-VI compounds. IV-VI active layers are also of interest for room temperature operational IR devices because IV-VI materials have significantly smaller Auger coefficients than the III-V or IIVI materials [2]-[4], a property that could be utilized to enhance IR laser and photodetector performance [5]. Thus, the heterocrystalline epitaxial integration of rock-salt lead chalcogenides with zincblende II-VI and III-V semiconductors on commercially available III-V semiconductor substrates can potentially enable a wide range of novel material properties and device applications.

In this study, heterovalent and heterocrystalline structures composed of InSb, CdTe, and PbTe layers were grown on ¼ 2” (001) InSb substrates in a single-chamber MBE system. High-quality materials were achieved using careful control of the growth conditions at the interface between two different crystal structures with matched lattice constants in plan. For the PbTe/CdTe heterostructures (Fig. 1), CdTe growth was initiated on the Cd-terminated InSb surface by opening the Te cell shutter, whereby a (2×1) surface reconstruction was observed immediately. The surface reconstruction during the PbTe growth on CdTe, which eventually transitioned to a streaky (1×1) pattern during the PbTe growth when a Te surface soak of 60 seconds was used between the bottom CdTe buffer and the PbTe layer, suggests that the common Te atoms at the interface help to promote layer-by-layer growth of PbTe. This contrasts the case of PbTe grown directly on InSb, where the use of a Te overpressure on InSb resulted in a spotty surface reconstruction throughout the growth. PL properties of the samples were tested between 13 to 300 K, with an increase in peak emission energy with temperature. Crystal quality was determined from XRD and TEM.

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