Monday Afternoon Poster Sessions, September 23, 2019

MBE

Room Bar/Living Room - Session MBE-MoP

MBE-Poster Session

MBE-MoP1 Simultaneous Topographical And Electrochemical Mapping Using Scanning Ion Conductance Microscopy – Scanning Electrochemical Microscopy, *G. Mendoza,* Park Systems, Mexico*;* ***Byong Kim****, K. Lee,* Park Systems

Lately, scanning ion conductance microscopy (SICM), has emerged as a versatile non-contact imaging tool. To obtain spatially-resolved electrochemical information, scanning electrochemical microscopy (SECM), also known as the chemical microscope, has been developed [1]. In hybrid SICM-SECM techniques, the SICM compartment provides the accurate probe-sample distance control, while the SECM compartment measures the faradaic current for electrochemical information collection [2]. In this work, we demonstrate the use of an Atomic Force Microscopy (Park NX10) in combination with an ammeter for concurrent topography imaging and electrochemical mapping. The SICM-SECM probe consisted of a Au crescent electrode (AuE) on the peripheral of a nanopipette. High resolution probe-substrate distance control was obtained by the ion current feedback from SICM, while simultaneous electrochemical signal collection was achieved via the AuE from SECM. As a proof-of-concept experiment, an Au/Pyrex pattern standard sample was imaged with the SICM-SECM technique. The Au bar and the Pyrex substrate were clearly resolved from the SICM topography image, with the bar height and pitch width closely matching the actual values. In terms of the electrochemical property mapping, higher Faradaic current was seen when the probe was scanned over Au bar as a result of redox cycling, while lower Faradaic current was observed when the probe was over Pyrex substrate due to hindered diffusion (Figure 1). The capability of the SICM-SECM technique described here holds promise of many applications in the field of electrochemistry, material science and nanoengineering.

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MBE-MoP2 Doping and Surfactant Behavior of Gallium in Low-Temperature Silicon and Germanium Growth, ***Amanda Lemire****, J. Manninen, J. Chivers, K. Grossklaus, T. Vandervelde,* Tufts University

Silicon-germanium-tin (SiGeSn) compounds are interesting as potential direct bandgap CMOS compatible materials. Sn precipitation and surface segregation occur for growth and annealing temperatures substantially below standard Si and Ge growth temperatures [1]. Molecular beam epitaxy (MBE) growth at the low temperatures needed to achieve significant Sn incorporation can also result in a degradation in Si and Ge film quality. Understanding and improving the low temperature growth of Si and Ge may improve SiGeSn film quality for optoelectronic applications. Gallium has been investigated by crystallographic techniques as a dopant and surfactant in low-temperature Si epitaxial growth [2,3,4], and as a dopant in GeSn [1]. In this work we investigate the relationship between pyrometer calibrated MBE growth temperature (150°C - 600°C), growth rate, and the doping/surfactant behavior of Ga in low temperature Si, Ge, and SiGeSn epitaxy, paying particular attention to film electronic and optical properties. Changes in surface roughness as determined by AFM are used to indicate whether Ga provides a beneficial surfactant effect. Ga incorporation as a dopant is investigated by Hall Effect measurements. Film optical properties are measured by variable angle spectroscopic ellipsometry. Changes in crystalline structure and quality resulting from the presence of the Ga and from Sn incorporation are measured by XRD.

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MBE-MoP3 Buffer layer growth for Ⅲ-Ⅴ on Si substrates using Molecular Beam Epitaxy, ***Geun-Hwan Ryu****,* Inha University, South korea*; J.D. Song, S.Y. Ahn, N.G. Hong,* Korea Institute of Science and Technology, South Korea*; H.Y. Ryu,* Inha University, South Korea*; W.J. Choi,* Korea Institute of Science and Technology, South Korea

As we approach the physical limits of silicon in the semiconductor industry, there have been many attempts to overcome these obstacles. One of these attempts is to use III-V semiconductors due to its superior physical characteristics. However, epitaxial growth of III-V materials have been limited to III-V substrates such as GaAs and InP. In order to take advantage of Si substrates, which has been used for decades in the semiconductor industry due to its ease of use, low cost, availability in large areas and physical properties such as thermal conductivity, a well-constructed buffer layer is critical for heteroepitaxy of III-V materials. This buffer layer may overcome defects such as threading dislocation and anti-phase boundaries which are normally associated with heteroepitaxial growth. Here, we demonstrate the growth of a buffer layer using a seed layer and SPS to minimize defects.

Fig. 1(a) shows the structure of III-V on Si using a seed layer and Short-Period Superlattice (SPS). The AlAs seed layer is grown at a high temperature while the AlAs/GaAs SPS is grown at a low temperature. The buffer layer is terminated by an InGaAs/GaAs Defect Fiter Layer (DFL) structure. The surface roughness measured by Atomic Force Microscopy (AFM) was 2 nm (root mean square) (Fig. 1(b)). Fig. 1(c) shows the cross-section of the buffer layer using Transmission Electron Microscopy (TEM). It is apparent that the surface is improved in AlAs/GaAs SPS and the dislocation is decreased InGaAs/GaAs DFL. Fig. 1(d) shows the result of Etch-Pit Density (EPD) measurement using KOH solution and Optical Microscopy (OM). Average EPD value was 3,000 /cm^2. As a result, we expect to grow low-cost, high-efficiency devices by growing III-V compound semiconductor on Si substrates.

MBE-MoP4 Influence of Strain on InAsSb Composition, ***Wendy Sarney****, S. Svensson, A. Leff,* CCDC Army Research Laboratory*; D. Donetsky,* Stony Brook University

A mixed group-V semiconductor's composition results from a complex interaction of each group V element with each other and with the group IIIs. Furthermore, since group V fluxes are controlled thermally and by valves or flow controllers, precise control is overall very difficult in mixed group V alloys compared with mixed group III alloys.

MBE growth conditions, such as the group V absolute fluxes and flux ratios, substrate temperature, group III growth rates, and the presence of surfactants all affect the composition of InAsSb [1-4]. The co-dependence of each of these parameters on each other is not well established. The sign and degree of strain also influences incorporation.

In one example, we grew two series of InAsSb samples onto GaSb at a range of temperatures using flux ratios known to produce Sb compositions of ~50% and 9% (near lattice match) at 415° C. The higher composition samples are relaxed and unaffected by strain. The samples grown near lattice match resist the growth temperature-induced changes in composition, where the composition levels out for a range of ~75° in substrate temperature.

We also observed that the group V incorporation in InAsSb for the same Sb/As ratio varies depending on the degree and sign of the strain.

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MBE-MoP5 Grading for Control of the Lattice Constant and Bandgap, as well as the Charge Distribution and Band Offsets at Interfaces, ***Wendy Sarney****, S. Svensson, A. Leff,* CCDC Army Research Laboratory*; D. Donetsky, G. Kipshidze, L. Shterengas, G. Belenky,* Stony Brook University

Compositional grading allows growth of bulk unstrained, unrelaxed InAsSb across the composition spectrum onto GaSb [1, 2]. Transmission electron microscopy (TEM), for example in Fig 1, shows that GaAlInSb grades behave as an ideal illustration of the principles outlined by Tersoff [3]. This mitigates the grade's residual strain, and the in-plane lattice constant at the top of the graded region equals the native unrelaxed lattice constant of the epilayer. Proper grading allows for virtual substrates with x-ray peak widths that are on the same order as the substrate and are coincident to the active epilayer peak (example, Fig 2).

There is limited work for the optimization of grading rates, strain offsets at the grade/virtual substrate interface, and grading species selection. TEM and x-ray diffraction data that demonstrate how these choices affect the epilayer quality. We also studied the practicality of extending Tersoff's methodology to other materials, such as InGaAs, and group V grades such as InAsSb and GaAsSb.

Another application of composition grading is maintaining a constant lattice constant while controlling charge distributions and band offsets at interfaces. Such grading requires precise composition control, and unlike the Tersoff grades, ideally occurs without dislocation formation. We will discuss our findings related to such grades.

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MBE-MoP6 Estimation of the Lateral Dimensions of Epitaxial CdSe/ZnSe Fractional Monolayer Quantum Dots*, **Carlos Basilio**,* Cinvestav-IPN, México*; I. Hernández-Calderón,* CINVESTAV, México

CdSe fractional monolayer quantum dots (FMQDs) are formed by the epitaxial deposit of a submonolayer (coverage Θ<1), they present 3D confinement, and their emission is in the blue spectral range. The photoluminescence (PL) spectra of these FMQDs present excitonic features that need a clear explanation [1, 2]. Their structural properties are not well known; its characterization by transmission electron microscopy, to determine their lateral dimensions, represents a great experimental challenge, due to their ultra-thin thickness of just one monolayer (ML) and the relatively low contrast between ZnSe and CdSe. Therefore, it is very important to use indirect methods that allow estimating the lateral sizes and density of these FMQDs.

In this work, we present the PL characterization and theoretical modeling of CdSe/ZnSe FMQDs with a nominal coverage of ≈0.5 ML. The quantum dots were grown by atomic layer epitaxy within a ZnSe matrix grown by molecular beam epitaxy on a GaAs (001) substrate at ≈275 °C growth temperature. The low temperature (19 K) PL spectra show an intense excitonic emission which typically consists in a double peak in the 2.752 to 2.760 eV energy range, with narrow full widths at half maximum, as shown in Figure 1. The excitonic spectra suggest small distributions in form, size, and composition of the CdSe/ZnSe FMQDs. To model the FMQDs we employed the factorized envelope approximation [3]. For simplicity, we considered that the FMQDs have a rectangular shape with L_x and L_y of similar sizes due to the C_4 symmetry of the (001) substrate surface. The calculations indicate that the excitonic emission can be correlated to lateral dimensions in the 4 to 5 nm range, see Figure 2, which result in a FMQDs density of $3X10^{12}$ cm^{-2} for a CdSe coverage of ≈0.5 ML.

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MBE-MoP7 Study of Conduction Mechanism using Temperature-Dependent Current-Voltage Measurements for GaAsSb Nanowire and Effect of In-situ Annealing*, **Mehul Parakh**, S. Johnson, R. Pokharel, S. Devakoa, P. Ramaswamy, J. Li, S. Iyer,* North Carolina A & T State University

This work presents the first observation of space charge limited conduction (SCLC) mechanism in intrinsic GaAsSb nanowires (NW) grown by Ga-assisted molecular beam epitaxy and the effect of post-growth in-situ annealing in an ultra-high vacuum on the conduction mechanism in the NWs. Current-voltage (I-V) measurements on single NW (using Conductive Atomic Force Microscopy) and ensemble NWs (using two probe method) exhibited linear behavior at lower bias transitioning to a power law behavior at higher bias, where the dominance of injected carriers over thermally generated charge carriers was observed. Temperature-dependent analysis on as-grown ensemble NW device in SCLC region yielded a wide trap density of 1016 cm-3 distributed over a wide energy range in the band gap compared to the reduced trap density of 7 * 1014 cm-3 in in-situ annealed NW ensemble at a trap energy level of 0.12 eV located below the band edge, suggesting annealing in ultrahigh vacuum is an effective approach for the annihilation of the traps. The trap density is attributed to be originating from Ga vacancy and GaSb defect level in III-V ternary material system. Increased PL intensity and red shift with reduced full-width half maxima at 4K were observed for in-situ annealed NWs compared to as-grown NWs. This can be correlated to better compositional homogeneity and annihilation of traps in the annealed NWs. Asymmetrical broadening and decreased TO/LO mode observed in the room temperature Raman spectra of as-grown NWs correlates well to more strain incorporation and presence of disorder, leading to the higher density of traps compared to the in-situ annealed NWs.

MBE-MoP8 N-type Doping of GaAs Nanowires using GaTe Source Grown by Self Assisted Molecular Beam Epitaxy*, **Shisir Devkota**, M. Parakh, P. Ramaswamy,* North Carolina A & T State University*; L. Reynolds,* North Carolina State University*; S. Iyer,* North Carolina A & T State University

N-type doping of GaAs nanowires (NWs) grown by molecular beam epitaxy (MBE) on (111) Si substrate using gallium telluride (GaTe) as a dopant source is successfully reported. A detailed study has been carried out to assess the impact of variation of GaTe source cell temperature on morphology, electrical and optical properties of NWs. Tellurium (Te) doping in the NWs was investigated for GaTe cell temperatures ranging from 200°C to 570°C. The variations in the optical, electrical and morphological characteristics with cell temperature were investigated using low-temperature photoluminescence (PL), atomic force microscopy (AFM) and scanning electron microscopy (SEM). Te incorporation in our NWs was attested by the presence of 4K PL shoulder peak, which is ~ 0.18 eV red shifted with respect to GaAs band to band transition at 1.50 eV. Moreover, a shift in the PL peaks, variation in their full width maxima and corresponding variation in the I-V characteristics from AFM were used to ascertain the increase in Te incorporation in the NWs with increasing cell tempature. Best fitting of the simulated I-V curves with the experimental data on a single NW obtained from AFM yielded the highest carrier concentratining of $2.2*10^{17}/cm^3$ with a carrier mobility of 7500 cm^2/ Vs. The highest responsivity of Te doped NW/p-Si was found to be 64 mA/W. Transmission electron microscopy (TEM) investigations of these NWs will also be presented.

MBE-MoP9 Effect of Gold Coatings on Quantum Dot Emission*, **Ariel Weltner**, C. Schuck, K. Vallejo, K. Sautter, T. Garrett, D. Tenne, P. Simmonds,* Boise State University

We grow tensile strained quantum dots (TSQDs) by depositing GaAs on InAlAs(111)A buffer layers lattice-matched to InP(111)A substrates. Tensile strain of 3.7% is imposed due to the difference in lattice constant between the two materials. The unusual presence of tensile strain in these GaAs QDs lowers their band gap and red-shifts their light emission further into the infrared. The outcome is TSQDs that emit light at energies below the bulk band edge of GaAs.

One of the applications for these high symmetry TSQDs on (111)-oriented surfaces is as entangled photon sources. The single photon spectroscopies used to demonstrate entanglement require that the photon collection efficiency of our measurements be as high as possible. During photoluminescence (PL), our TSQDs emit photons in all directions. One way to increase photon collection efficiency is to insert a mirror below our TSQDs to reflect the photons emitted downward (towards the substrate) back to the sample surface, where they can be collected in the spectrometer.

For conventional InAs/GaAs(001) QDs, this mirror is typically a distributed Bragg reflector (DBR), consisting of a superlattice of alternating GaAs/AlGaAs layers. To create a similar DBR in our InP-based structures would be challenging for two reasons. First, the GaAs TSQDs emit light at λ= 1000–1100 nm (at 11 K). Second, our samples would require lattice-matched InGaAs and InAlAs, which do not have a particularly strong index contrast. The combination of these factors means that each period of the InGaAs/InAlAs superlattice would need to be significantly thicker than conventional GaAs/AlGaAs DBRs, with even more periods required to reach even low reflectivity. High quality InGaAs/InAlAs growth on InP(111)A requires growth rates of ~170 nm/hr, which estimates a total growth time for DBRs of 8-10 hours.

A cheaper, easier, and less time-consuming approach is to take advantage of the long-wavelength emission from our GaAs TSQDs. At 11 K, the TSQD photon emission energy (<1.24 eV) is less than the band gap of either InAlAs (1.53 eV) or InP (1.42 eV), allowing us to simply use a gold reflective coating on the backs of the substrate. The InAlAs barriers and InP substrate are transparent to the TSQD emission, allowing photons to be reflected by the gold coating, back up through the sample, and into the PL collection optics.

Preliminary results on GaAs TSQDs show a clear increase in PL intensity for coated vs uncoated samples. We will present results showing how gold deposition thickness affects PL intensity and how the gold-InP interface may be optimized to maximize reflectivity.

MBE-MoP10 Nanostructure Mapping of GaAs and Ge (111)A Quantum Dots using Island Scaling and Radial Distribution Scaling Analysis, ***Trent Garrett**, H. Henry, K. Sautter, K. Vallejo, C. Schuck, A. Weltner, E. Jankowski, P. Simmonds,* Boise State University

Tensile strained quantum dot (TSQD) nanostructures present new and exciting properties, including a reduction in the band gap [1], Type I and II carrier confinement [2], and an opportunity for entangled photon emission due to low fine structure splitting [1]. These interesting TSQD properties enable potential applications in quantum, optic, and information devices [1]. We utilized molecular beam epitaxy (MBE) to synthesize self-assembled GaAs and Ge TSQDs on InAlAs(111)A surfaces. We control TSQD structural properties (i.e. volume, height, and diameter) by changing basic MBE parameters such as growth temperature, rate, and deposition amount [2]. Understanding how these parameters affect QD properties is key to successfully integrating these nanostructures into future devices. We use island scaling (IS) and radial distribution scaling (RDS) to determine how variations in MBE growth parameters and materials affect TSQD structural properties. RDS enables us to qualitatively determine the diffusion coefficient; as well as the probability of finding TSQDs at a certain distance from an arbitrary origin [3]. Although RDS has been used extensively to study traditional compressively strained QDs [4], this represents the first use of IS and RDS to explore the growth of Ge and GaAs TSQDs on InAlAs(111)A. We have seen marked differences between Ge and GaAs TSQD self-assembly, despite the fact that from the point of view of tensile strain, these two TSQD systems are similar.

We will present IS and RDS curves for Ge and GaAs TSQDs grown at 535 °C with depositions ranging from 0.2–0.6 bilayers and 3–4.5 monolayers, respectively. Compared to GaAs TSQDs, our IS results suggest narrower size distributions for Ge TSQDs, while RDS displays higher probabilities of finding Ge TSQDs closer to an arbitrary origin. This investigation will allow us to more fully understand the differences in the processes by which Ge and GaAs TSQDs self-assemble, leading to even closer control over their structural properties.

MBE-MoP11 Optical Properties of InAs/GaAsSb Sub - Monolayer Quantum Dots with Various Sb Compositions, ***Minseak Kim**, H.J. Jo, J.S. Kim,* Yeungnam University, Republic of Korea*; Y. Kim, S.J. Lee,* Korea Research Institute of Standards and Science, Republic of Korea*; C. Honsberg,* Arizona State University

We have investigated optical properties of the InAs/GaAsSb sub-monolayer (SML) quantum dots (QDs) by photoreflectance (PR) and photoluminescence (PL) spectroscopy. To form SML-QDs, a 0.5 ML-thick InAs layer was grown on the GaAs buffer layer and subsequently a 2.5 ML-thick GaAsSb layer (Sb compositions; 0 ~ 19.4%) was followed to cover the InAs layer. The SML-QDs layer consists of 5 cycles of InAs (0.5 ML)/GaAsSb (2.5 ML). After formation of the SML-QDs, 10 nm-thick GaAs layer was used as a spacer layer. 8 periods of SML-QD layers were embedded in each sample.

Fig. 1 and 2 showed the low temperature PL and PR spectra for InAs/GaAsSb (0.5 ML/2.5 ML) SML-QDs, respectively. As increasing the Sb composition, PL emission peak position drastically red-shifted due to the decreasing of the potential barrier height. In the PR spectra, we observed not only QDs related optical transitions but also GaAs band-to-band (E_{GaAs}) and unidentified transitions (UT) as shown in Fig. 2. The amplitude of PR spectra related to SML-QDs transitions are relatively larger than those of the GaAs. This phenomenon can be attributed to the fact that the photo-generated carriers efficiently confined in the SML-QD region. In Addition, we observed sharp transition features between GaAs and QDs due to the interface electronic states of InAs/GaAsSb/GaAs.

MBE-MoP12 LATE NEWS: Epitaxial Growth of Relaxed InGaN Films on ZnO Substrate by Plasma-Assisted Molecular Beam Epitaxy, ***Kamruzzaman Khan**, E. Ahmadi,* University of Michigan

InGaN alloys are attractive for optoelectronic and electronic applications and have been studied extensively for light emitting diodes and lasers in the last two decades. Varying In content in ternary InGaN alloys allows band gap engineering in a wide range of energies from 0.7 eV to 3.4 eV. Nonetheless, growth of large In content InGaN alloys have been challenging due to significant difference in thermal stability of InN and GaN, in addition to large lattice mismatch between InGaN and GaN. The latter limits the critical thickness of InGaN films grown on GaN after which InGaN relaxes plastically via formation of defects.

The above-mentioned challenges have motivated scientists to develop relaxed InGaN as pseudo-substrate. Growth of $In_zGa_{1-z}N$ on relaxed $In_xGa_{1-x}N$ substrate (z>x) is favorable due to smaller lattice mismatch which will result in larger critical thicknesses. Multiple groups have studied growth of relaxed InGaN films on GaN substrates. It has been shown that achieving full or even partial relaxation of an InGaN layer via an abrupt transition results in high density of V-defects and pits that degrade the structural and optical quality of the layer. A fully relaxed $In_{0.1}Ga_{0.9}N$ layer has been achieved on GaN by grading InGaN [1]. However, it has been shown that the relaxation occurs through formation of threading dislocations.

In this work, we have investigated growth of InGaN on ZnO substrates using plasma-assisted molecular beam epitaxy (PAMBE). InGaN and ZnO possess same stacking order. Moreover, based on Vegard's law $In_{0.2}Ga_{0.8}N$ is lattice matched to ZnO in c-plane [2] which is promising for growth of high quality relaxed InGaN buffer layers. Also, PAMBE is a relatively low temperature growth technique which should suppress the formation of unwanted In_2O_3interlayer because of reaction between O and InGaN at the interface enabling smooth growth on these lattice-matched but chemically dis-similar materials. Here, the impact of In and Ga metal fluxes and substrate temperature on ZnO-InGaN interface quality, InGaN surface morphology and InGaN composition have been studied. We have also compared the ZnO substrate polarity (Zn-face vs O-face) on the InGaN film quality.

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MBE-MoP13 LATE NEWS: Molecular Beam Epitaxy of AlN and GaN Nanocrystals: Towards High Efficiency Deep Ultraviolet LEDs, ***Yuanpeng Wu**, A. Pandey, D.A. Laleyan, X. Liu, P. Wang, C. Ahn, M. Kira, Z. Mi,* University of Michigan

To date, it has remained difficult to achieve efficient LEDs operating in the ultraviolet (UV)-C band due to several critical challenges: 1) poor p-type conduction of AlN and the resulting extremely low carrier (hole) injection efficiency, 2) very low quantum efficiency due to the presence of high densities of defects, and 3) poor light extraction efficiency associated with transverse-magnetic (TM) polarized emission for Al-rich AlGaN. Dislocation-free AlGaN nanocrystals have recently shown great promise to address these critical challenges. With the use of plasma-assisted molecular beam epitaxy (MBE), we have performed extensive studies of Mg-doped AlN nanocrystals. We show that, the use of N-rich conditions can significantly enhance Mg-dopant incorporation while suppressing N-vacancy related defect formation. The formation of Al-vacancy related defects, on the other hand, can be minimized by optimizing the growth temperature. Under optimized growth conditions, we demonstrate that large densities Mg-dopant ($\sim 1\times10^{20}cm^{-3}$) can be incorporated in AlN. The resulting high concentrations of Mg-dopants lead to the formation of Mg impurity band and efficient hole hopping conduction. At room temperature, we measured free hole concentrations up to $6\times10^{17}cm^{-3}$, which is nearly seven orders of magnitude higher than that of Mg-doped AlN epilayer.

We have further investigated the epitaxy, fabrication, and characterization of large area AlN nanocrystal LEDs. The device exhibits strong electroluminescence emission at ~210 nm and excellent current-voltage characteristics, with a turn-on voltage ~6 V. The ideality factor is estimated to be ~4 and further increases with applied voltage, due to the tunneling of holes from the Mg impurity band to the valence band. We have also demonstrated deep UV LEDs by incorporating single and double monolayer GaN active regions, respectively. Such dislocation-free GaN monolayer structures can exhibit transverse-electric (TE) polarized emission in the deep UV spectrum and have reduced quantum-confined Stark effect. The controlled formation of single and double monolayer GaN was further confirmed by HAADF-STEM analysis. AlN nanowire LEDs with GaN monolayers incorporated were further fabricated. For the monolayer GaN sample, the emission peak is at 238 nm. The light intensity increases near-linearly with increasing current. The peak emission wavelength stays nearly invariant with increasing current, due to the extreme quantum-confinement. Work is currently in progress to achieve deep UV LEDs with high power operation by enhancing the light extraction efficiency utilizing AlGaN photonic nanocrystals and by optimizing fabrication process.

MBE-MoP14 LATE NEWS: Graphene/III-V Hybrid Diodes and Optical Devices by Heteroepitaxy, *R. Yao, B. Zheng,* University of Massachusetts Lowell*; H. Kum, Y. Kim, S. Bae, J. Kim,* Massachusetts Insititute of Technology*; H. Zhang,* University of Massachusetts Lowell*; S. Xia,* Georgia Institute of Technology*; **Wei Guo**,* University of Massachusetts Lowell

Graphene, an atomic monolayer formed by carbon hexagons, has recently emerged as a novel material with unique electrical and optical properties. In order to change the optical properties of graphene, a gate voltage applied to this capacitor causes carriers to accumulate or deplete on the

graphene sheet, change the graphene optical conductivity and switch the intraband absorption of the graphene. This change in absorption modulates the intensity of light travelling through it. Operation speed can be increased by using a thicker gate oxide, but the resulting lower capacitance leads to a smaller graphene optical conductivity change and reduced modulation depth and efficiency.

In this work, we demonstrate a hybrid graphene/GaAs diode and efficient modulation of THz radiations. The hybrid modulator diode is achieved by heterogeneous integration of graphene with GaAs heterojunctions enabled by the remote epitaxy technology, where graphene is placed at the depletion region of the GaAs p-n junctions, sandwiched between n-type GaAs top junction and p-type GaAs bottom junctions. The operation principle of the hybrid modulator diodes is similar to the modern semiconductor electro-absorption modulators (EAM), where the active quantum well (QW) region in placed in the III-V p-n junctions and p-n junction is electrically biased to change the absorption spectrum of the active QW region. In the hybrid modulator diode, the bias voltage of the GaAs p-n junction diode can effectively tune the Fermi level in the hybrid junction by using the depletion electric field or current injection. Figure 1b shows the reflection high-energy electron diffraction (RHEED) pattern of the GaAs layers grown on 2D graphene, it is found that a streaky GaAs 2x RHEED pattern is obtained after 400 nm GaAs remote epitaxy growth on graphene. The streaky and sharp pattern indicates smooth GaAs (100) surfaces resulted from the remote epitaxy growth. A micrograph image of the as-grown sample is shown in the inset of Figure 1b, and a mirror-like surface is obtained in the graphene region.

The details of the device characterizations over the broad spectrum from NIR to THz will be presented.

MBE-MoP15 LATE NEWS: The Role of Intervalley Phonons in Hot-Carrier Transfer and Extraction in InAs/AlAs$_{0.16}$Sb$_{0.84}$ Quantum-Well Solar Cells, *V.R. Whiteside, H. Esmaielpour,* ***Kyle R. Dorman****, T.D. Mishima,* University of Oklahoma*; D.K. Ferry,* Arizona State University*; M.B. Santos, I.R. Sellers,* University of Oklahoma

Much of the recent work in hot-carrier solar cells has focused on inhibiting hot-carrier relaxation through the creation of a phonon bottleneck, whereby the reabsorption of LO phonons at high excitation power reduces hot-carrier thermalization rates. We present a different approach in which the band structure of the constituent materials is utilized to store and transfer hot electrons in the upper L and X valleys of InAs quantum-well layers in a superlattice absorber, and then extract the carriers via energy selective n-Al$_{0.35}$In$_{0.65}$As and p-AlAs$_{0.16}$Sb$_{0.84}$contact layers [1].

The electro-optical properties of p-i-n diodes with an InAs/AlAs$_{0.16}$Sb$_{0.84}$ superlattice absorber were characterized with simultaneous continuous-wave photoluminescence and monochromatic current density-voltage measurements. The experiments revealed a stable hot-carrier population not only at a relatively low excitation power, but which was nearly independent of excitation power. This behavior is attributed to preferential scattering of high-energy electrons from the Γ valley to the upper metastable satellite valleys of the InAs conduction band, which inhibits carrier thermalization via LO phonon emission. Both a high electric field and optical excitation are shown to enable hot-carrier generation in the InAs quantum wells. However, the extraction of electrons from the absorber to the n-Al$_{0.35}$In$_{0.65}$As layer is inhibited by the mismatch in the L to Γ valley degeneracy across the InAs/Al$_{0.35}$In$_{0.65}$As interface. A strength of this approach is that hot-carrier extraction is facilitated by well-established physical effects, namely intervalley scattering and the Gunn effect. Luminescence data provide evidence of a stable hot carrier population, which is shown to impact the performance of the device under practical operating conditions without the need for a phonon bottleneck. As such, this approach provides a viable route towards a hot-carrier solar cell.

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Garrett, T.: MBE-MoP10, **3**; MBE-MoP9, 2
Grossklaus, K.: MBE-MoP2, 1
Guo, W.: MBE-MoP14, **3**
— H —
Henry, H.: MBE-MoP10, 3
Hernández-Calderón, I.: MBE-MoP6, 2
Hong, N.G.: MBE-MoP3, 1
Honsberg, C.: MBE-MoP11, 3
— I —
Iyer, S.: MBE-MoP7, 2; MBE-MoP8, 2
— J —
Jankowski, E.: MBE-MoP10, 3
Jo, H.J.: MBE-MoP11, 3
Johnson, S.: MBE-MoP7, 2
— K —
Khan, K.: MBE-MoP12, **3**
Kim, B.: MBE-MoP1, **1**
Kim, J.: MBE-MoP14, 3
Kim, J.S.: MBE-MoP11, 3
Kim, M.: MBE-MoP11, **3**
Kim, Y.: MBE-MoP11, 3; MBE-MoP14, 3
Kipshidze, G.: MBE-MoP5, 1
Kira, M.: MBE-MoP13, 3
Kum, H.: MBE-MoP14, 3
— L —
Laleyan, D.A.: MBE-MoP13, 3
Lee, K.: MBE-MoP1, 1
Lee, S.J.: MBE-MoP11, 3
Leff, A.: MBE-MoP4, 1; MBE-MoP5, 1
Lemire, A.: MBE-MoP2, **1**
Li, J.: MBE-MoP7, 2
Liu, X.: MBE-MoP13, 3
— M —
Manninen, J.: MBE-MoP2, 1
Mendoza, G.: MBE-MoP1, 1
Mi, Z.: MBE-MoP13, 3
Mishima, T.D.: MBE-MoP15, 4
— P —
Pandey, A.: MBE-MoP13, 3
Parakh, M.: MBE-MoP7, **2**; MBE-MoP8, 2
Pokharel, R.: MBE-MoP7, 2
— R —
Ramaswamy, P.: MBE-MoP7, 2; MBE-MoP8, 2
Reynolds, L.: MBE-MoP8, 2
Ryu, G.H.: MBE-MoP3, **1**
Ryu, H.Y.: MBE-MoP3, 1
— S —
Santos, M.B.: MBE-MoP15, 4
Sarney, W.: MBE-MoP4, **1**; MBE-MoP5, **1**
Sautter, K.: MBE-MoP10, 3; MBE-MoP9, 2
Schuck, C.: MBE-MoP10, 3; MBE-MoP9, 2
Sellers, I.R.: MBE-MoP15, 4
Shterengas, L.: MBE-MoP5, 1
Simmonds, P.: MBE-MoP10, 3; MBE-MoP9, 2
Song, J.D.: MBE-MoP3, 1
Svensson, S.: MBE-MoP4, 1; MBE-MoP5, 1
— T —
Tenne, D.: MBE-MoP9, 2
— V —
Vallejo, K.: MBE-MoP10, 3; MBE-MoP9, 2
Vandervelde, T.: MBE-MoP2, 1
— W —
Wang, P.: MBE-MoP13, 3
Weltner, A.: MBE-MoP10, 3; MBE-MoP9, **2**
Whiteside, V.R.: MBE-MoP15, 4
Wu, Y.: MBE-MoP13, **3**
— X —
Xia, S.: MBE-MoP14, 3
— Y —
Yao, R.: MBE-MoP14, 3
— Z —
Zhang, H.: MBE-MoP14, 3
Zheng, B.: MBE-MoP14, 3