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MBE-Poster Session

MBE-MoP-1 Hydrogen Permeation Behavior of BN film, ***Motonori Tamura,*** The University of Electro-Communications, Japan

The hydrogen permeation behavior of BN-coated Type 316L stainless steel was investigated. In comparison with TiN and SiC films, the BN (boron nitride) film, deposited by molecular beam epitaxy (MBE), was effective to reduce the rate of hydrogen permeation through stainless steel (Fig. 1).

Hydrogen-permeation tests were performed on the coated stainless steel samples. These tests were based on the differential-pressure methods in ISO15105-1.

The permeation of hydrogen through solid materials involves a series of steps including adsorption, dissociation, diffusion, and recombination coupled with desorption.

The permeability, Q, is generally defined by the expression

$Q = J\, d / A\, (dP)^{n}$

where J is the permeation flux of hydrogen through a sample of area A and thickness d, under a partial pressure gradient (dP) across the sample called the driving pressure. The exponent n represents different permeation regime s : diffusion- limited and surface- limited when n = 0.5 and 1, respectively.

The double- logarithmic plots show ed that the two sets of data of BN- and TiN-coated samples were linearly related. The exponent n showed a value of 0.48 – 0.53 at 573 – 773 K, which indicated that hydrogen passed through the samples in the diffusion- limited permeation mode.

MBE-MoP-3 Growth of Pure Wurtzite InGaAs Nanowires for Photovoltaic and Energy Harvesting Applications, ***Hangkyu Kang,*** *M Baik,* Yonsei University, Republic of Korea*; B Yoo,* Hanyang University, Republic of Korea*; J Song,* Korea Institute of Science and Technology, Republic of Korea*; M Cho,* Yonsei University, Republic of Korea

Vertically aligned and highly densified InGaAs nanowires were grown on Si (111) substrates by Au-assisted molecular beam epitaxy, and antireflection characteristics of the InGaAs nanowires were characterized. The bandgap of InGaAs NWs was tuned by varying the In to Ga ratio; the compositions of Ga and In were controlled to adjust a bandgap to ~1.0 eV. The obtained nanowires were vertically aligned with a diameter of ~20 nm near the top and ~44 nm at the bottom, a slightly tapered morphology. This morphological shape can be formed because of the different surface diffusivities and affinities of In and Ga to the Au catalyst. By controlling the deposition conditions, InGaAs nanowires with no significant stacking defects, kinking, and bending were grown successfully on Si (111) substrates. High-resolution transmission electron microscopy studies showed that the InGaAs nanowires were grown with a pure wurtzite single crystalline structure with a maximum length of ~18 µm. Photo-reflectometry and spectroscopic ellipsometry measurements showed a significant reduction in the reflectance, less than ~5% for normal incidence in the wavelength range of 200-1700 nm and considerable reduction at incident angles of 30-70°, demonstrating the antireflection properties of the InGaAs nanowires. Furthermore, piezoelectric properties were observed in all the areas where InGaAs nanowires were grown for a contact area of 2 µm × 2 µm, as the growth direction was along the polar *c*-axis (<111> direction) of the hexagonal structure.

MBE-MoP-4 Effect of ex-situ Passivation of the GaAsSb Nanowires, *M Sharma, J Li, S Iyer,* ***Rabin Pokharel,*** North Carolina A&T State University

Semiconductor nanowires (NWs) due to their one-dimensional architecture result in unique electronic properties with a wide range of applications towards optoelectronic devices. The high aspect ratio enables a broader choice of the substrates attributed to better stress-strain management, enhanced optical light trapping due to multiple scattering at NW surface, and the possibility of implementing numerous heterostructures (axial, core-shell). Further, the large surface/volume ratio plays a pivotal role at the nanoscale in controlling optoelectronic properties of devices. A large density of surface state (D_{it}) results in pinning of the Fermi level and surface band bending leading to the formation of the non-radiative levels.[1] The surface effects can be minimized using in-situ or ex-situ passivation of the surface enabling enhanced device performance.

In this presentation, we report on ex-situ chemical passivation of GaAs, GaAsSb axial NWs grown on Si (111) via Ga-assisted molecular beam epitaxy. GaAsSb is an important material system due to a broad tunability of its bandgap encompassing the 0.94-1.55 µm wavelength in the near-infrared region. Normally, the in-situ passivation of this material system is accomplished by the growth of AlGaAs/GaAs shells, which need to be etched in order to make a metal contact at the tip of the NWs. The advantage of ex-situ lies in eliminating this extra step as a couple of monolayers of the passivation layer is sufficient to minimize the surface effects. The ex-situ chemical passivation of the NWs was performed using hydrazine-sulfide solution, which first removes the pristine layer along with a formation of one or two monolayers of GaN shell. The I-V characteristics of the passivated single GaAs (GaAsSb) NW exhibit three-orders of magnitude increase in current, while the 4K micro-photoluminescence (µ-PL) peak at 1.25 eV revealed an increase in the intensity by four-fold in comparison to the unpassivated NWs. These improvements are attributed to increasing in the non-depleted region in the NW, resulting in a reduction in the D_{it} and surface recombination velocity [2] by one (two) order of magnitude for GaAs (GaAsSb) NWs. Thus, the outer shell of a higher bandgap material has been used to move the surface states away from and charge confinement in the core of the NWs.

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MBE-MoP-5 Study of As-rich Interfaces with Exponentially Decaying As Content within InAs/AlSb Superlattices, ***Yunong Hu,*** *M Tam, Z Wasilewski,* University of Waterloo, Canada

Highly strained interfaces may exist between InAs and AlSb layers grown by MBE [1]. The composition and thickness of the interfacial layer influence strongly the electronic properties of InAs/AlSb based structures. However, they are hard to characterize and nominally identical growth run may give very different interfaces in different MBE systems.

In this work, we study the influence of As flux interruption procedure on the unintentional incorporation of As into AlSb layers. This effect can significantly alter the strain distribution in AlSb barrier by changing it into compositionally graded AlAsSb layer. In the first stage, the As flux temporal dependence was measured during mock growths, inside Veeco GEN10 MBE system using a beam flux monitor (BFM) at wafer position. A storage scope was used to record the BFM signal at 2ms intervals. When the As beam was interrupted, instead of abrupt flux drop, exponential decay was observed. An excellent fit was obtained using double exponent function (Fig. 1). As expected, very abrupt flux termination was observed with closing Sb shutter. Subsequently, three samples of 200Å/150Å InAs/AlSb superlattices with 5 repeats were grown on InAs(001) substrates at 420°C using As_2. Identical shutter/valve sequence was used as during the mock growths. When the deposition was switched from InAs to AlSb, at the shutter closure, the As cell valve setting was kept unchanged for sample A, decreased to achieve 80% flux reduction for sample B, and fully closed for sample C.

The dynamical simulations of the High- Resolution X-ray Diffraction (HRXRD) gave very good agreement with experiment assuming that the profile of arsenic content in the $AlAs_ySb_{1-y}$ barrier followed the experimentally measured As_2 flux during the mock growths (Fig.1). This included the $In_xAl_{1-x}As_ySb_{1-y}$ interfacial monolayer (ML) at the start of the barrier. No additional strain was introduced at the second interface. For the growth performed with As beam interrupted only by the shutter, we find that the barrier composition y is still at 6.8% at the ends of the 150Å barriers. A considerable amount of As is incorporated even when both valve and shutter were closed for As interruption during barrier growth. However, in this case, arsenic is mostly confined to the first 5MLs.

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MBE-MoP-7 The Characteristics of Phototransistor based on the Grown $MoSe_2$ by Molecular Beam Epitaxy, ***Yoon-Ho Choi,*** *J Jeong, G Kwon, H Kim,* Yonsei University, Republic of Korea*; H Kim,* Sungkyunkwan University, Republic of Korea*; M Cho,* Yonsei University, Republic of Korea

Transition metal dichalcogenides (TMDs) have been explored as the promising active layer for the optical and electronic devices because they have a bandgap corresponding to visible light range and the high mobility at the subnanometer thickness. We studied molecular beam epitaxy (MBE) method in order to grow uniform $MoSe_2$ on large area substrate. The high-purity Se and Mo were evaporated by e-beam evaporator and Knudsen cell, respectively. The quality of the film was confirmed by spectroscopic measurement. The chemical composition and elemental ratio were studied by high resolution X-ray photoelectron spectroscopy (HRXPS). Scanning transmission electron microscopy (STEM) was conducted to observe growth mechanism and Moirè pattern. The growth mechanism involves layer by layer growth, expanding the bilayer gradually on the covered monolayer with the deposition time in figure 1. We also observed that the localized strain is induced by grain boundary between rotational stacking layer and oriented stacking. The band alignment of the film was confirmed by ultraviolet photoelectron spectroscopy (UPS) and spectroscopic ellipsometry (SE): The grown $MoSe_2$ by MBE is n-type semiconductor, having the optical band gap as 1.39eV and the valance band as 1.10eV. In addition, we fabricated the phototransistor based on the grown $MoSe_2$. The device exhibited the fast rising and decay time, 6ms and 8ms, respectively, at wavelength of 532 nm in figure 2. The variable on/off current with gate bias and laser power was measured, indicating the excellent photoresponsivity. Finally, we have successfully grown the $MoSe_2$ film on amorphous SiO_2, demonstrating phototransistor device applications.

MBE-MoP-8 Experimental Determination of Band Overlap in Type II InAs/GaSb Superlattice based on Temperature Dependent Photoluminescence Signal*, J Huang, Y Zhang, Y Cao, K Liu, W Huang, S Luo, H Ji, T Yang,* ***Wenquan Ma****,* Institute of Semiconductors, Chinese Academy of Sciences, China

Type II InAs/GaSb superlattice (SL) material has been widely used to make infrared photodetectors. In addition, this material system may play a unique role for some fundamental studies like spin–orbit interaction, topological insulator, and novel exciton condensates. A fundamental parameter of the material [1,2], the band overlap at the interface between InAs and GaSb, should be known. We have determined the band overlap in type II InAs/GaSb SL structure based on the temperature dependent photoluminescence (PL) results of a short- wave SL sample. The band overlap value is treated as a temperature variable and is simulated by fitting the PL peak position using the 8KP method. It is found that the band overlap monotonically decreases from 0.325 to 0.225 eV when temperature is increased from 12 to 90 K [3]. The calculated e1-hh1 transition using the obtained band overlap data shows an agreement with the PL results of another SL sample.

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MBE-MoP-10 Significantly Enhanced Performances of 1.3 µm InAs/GaAs Quantum Dot Lasers by Direct Si-doping*, Z Lv, Z Zhang,* ***Tao Yang****,* Institute of Semiconductors, Chinese Academy of Sciences, China

Direct Si-doping into InAs/GaAs quantum dots (QDs) has shown dramatically enhanced photoluminescence of the QDs [1]. This Si-doping technology has been used to fabricate intermediate band QD solar cells and led to a markedly increased conversion efficiency of the cells from 11.3% to 17% [2]. In this work, we demonstrate significantly improved performances of 1.3 µm InAs/GaAs QD lasers using the direct Si-doing technology.

Two QD laser structures with the doping concentration of 1×10^{18} cm^{-3} and without any doing were grown by MBE. The active region of the two lasers consists of five stacked layers of InAs/GaAs QDs. Ridge waveguide lasers with a ridge width of 30 µm for the two laser structures were fabricated using standard wet etching and metallization techniques.

Figure 1 shows single-side CW power-current (P–I) curves of the two lasers with a cavity length of 2.5 mm, obtained at 20 °C. It can be clearly seen from the figure that the threshold current of the doped QD laser is as low as 53.7 mA, which is much smaller than for the undoped one (125.5 mA). The corresponding threshold current density for the doped laser is only 71.6 A/cm (14.3 A/cm^2 per QD layer), whereas it is 167.3 A/cm^2 (33.5 A/cm^2 per QD layer) for the undoped QD laser. In addition, the single-side slope efficiency is improved from 0.28 W/A for the undoped QD laser to 0.42 W/A for the doped QD laser.

This work was supported by the National Natural Science Foundation of China (No. 91433206).

Figure 1 S ingle-side CW P–I curves of the two QD lasers

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MBE-MoP-11 Effect of in-situ Annealing on the GaAsSb Nanowire-based Photodetector*, M Sharma, E Ahmad, M Parakh,* ***Rabin Pokharel****, S Iyer,* North Carolina A&T State University

Amongst the III-V nanowires (NWs) of different material systems, interest in GaAsSb NWs stems from the tunability of its bandgap encompassing the telecommunication wavelength in the near-infrared region. One-dimensional (NWs) architectures have attracted considerable attention due to its better stress-strain management, high aspect ratio enhancing optical trapping, ability to implement different heterostructures (axial, core-shell),and quantum confinements leading to devices with advanced functionalities. NWs exhibit large surface/volume ratio adversely impacting the device performance, which is attributed to surface related and other defect states. In this report, reduction of surface states effects by in-situ annealing along with in-situ surface passivation has been presented, and NW photodetector has been demonstrated.

GaAsSb axial (core) NWs have been grown on Si (111) via Ga-assisted molecular beam epitaxy. To minimize the effect of surface states, in-situ vacuum annealing (10^{-10} Torr) at 465º C followed by in-situ growth of AlGaAs/GaAs shell around the core have been carried out. These NWs exhibit a significant improvement in µ-photoluminescence (PL) peak intensity and electrical characteristics as compared to bare GaAsSb axial NWs, attributed to suppression of band tail states. The analysis of temperature-dependent µ-PL peak intensity for unannealed NWs revealed the presence of two non-radiative thermal energy levels, which reduced to a single level in annealed nanowires. This further attests to the suppression of band tail states on annealing.

Hence the device was fabricated using the in-situ annealed nanowires. The performance of the p-i GaAsSb/AlGaAs NW ensemble based photodetector (PD) device was assessed under an illumination of 540 nm with an intensity of 173 µW/cm^2. The I-V characteristics were found to be well explained considering Schottky contact (SC) at both ends of the NWs. The PD device exhibited a responsivity of 540 A/W with an external quantum efficiency of 1.25×10^5 %. The best fit of the COMSOL fitting to the experimental I-V graphs indicated that the high spectral responsivity could be attributed to two orders of magnitude increase in carrier concentration under illumination.

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MBE-MoP-12 Reduced Heating Effects in MBE Grown Nanowire Array LEDs*, S Yang,* McGill University, Canada*; A Tian,* St. Maximillian Kolbe CHS, Canada*;* ***Yongyuan Zang****,* McGill University, Canada

It has been theoretically demonstrated that junction temperature in nanowires can be significantly lower than that in bulk devices [1]. However, very little research has been reported on the thermal properties of nanowire LED devices. In this regards we have investigated the impact of the Joule heating of axial InGaN/GaN nanowire light-emitting diodes (LEDs) grown by molecular beam epitaxy (MBE) on Si (111) for the first time. In this study, four nanowire LEDs are spontaneous formatted under nitrogen rich conditions and nanowire with different geometries were obtained through different growth conditions.

Figure 1 shows the measured peak wavelength of the samples at the same injection level. It can been seen that the peak wavelength shows a red shift of ~ 40 nm for sample with high filling factor while only shows a red shift of ~ 20 nm for samples with low filling factor. Since the red shift is commonly considered as the evidence of the LED self-heating effect [2], therefore the Joule heating effect of nanowires is significantly reduced for less dense geometry. Also observed is the large inhomogeneous broadening of the active region interplay with the higher filling factor which can be attributed to rising temperature (Shown in the inset). A significant reduced EQE also can be observed in sample with high filling factor, as shown in Figure 2. These results indicated that the nanowire have a better thermal dissipation and conversion efficiency than conventional planar structures.

Based on the results in this work, a systematic simulation and theoretical model was presented for the first time to interpret all the thermal transport process of the nanowire LEDs.

Figure 2 Measured EQE for samples with different filling factor.

Figure 1 Peak wavelength of nanowire LEDs samples with different filling factor under different duty cycle at same injection level. The inset is the EL spectrum of nanowire led samples under cw injection with filling factor of 10% and 70% respectively.

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MBE-MoP-13 Effect of Column Diameter and Height on Optical Properties of Regularly Arranged GaN Nanocolumn Grown by rf-MBE, ***Hiroto Sekiguchi***, *Y Higashi, K Yamane, H Okada, A Wakahara,* Toyohashi University of Technology, Japan; *K Kishino,* Sophia University, Japan

GaN nanocolumns have a great potential in improving emission efficiency in the longer-wavelength due to dislocation filtering and strain relaxation [1]. The regularly arranged (RA) nanocolumns have been demonstrated on GaN layer, however, the selective area growth of nanocrystals on Si is required in terms of low-cost and large-area substrate. In this study, the effects of diameter and height on optical properties were investigated because it is important to know key points to obtain high crystalline nanocolumns.

The RA-GaN nanocolumns were fabricated on AlN/Si substrate by Ti-mask selective-area growth technique [2]. GaN nanocolumns with different height (350 and 700 nm) were prepared. Figure 1 shows the peak intensity of near-band edge (NBE) emission at RT as a function of diameter. While peak intensity at NBE drastically decreased with increasing the diameter for low height nanocolumns, high PL intensity kept at almost constant value up to 200 nm and dramatically decreased at 230 nm for high height nanocolumns. To understand this reason, CL measurement were performed (Fig. 2). While the ratio of strongly emitting nanocolumns decreased with increasing dimeter for 350 nm-height nanocolumns, it hardly decreased with increasing diameter for 700 nm-height nanocolumns. It would result from that threading dislocation did not propagate to the upper part in the 700 nm-height nanocolumn [1]. Next, the effect of diameter and height on yellow luminescence was investigated. While the ratio of yellow luminescence intensity to total PL intensity monotonically increased with increasing diameter for low height columns, it was constant at small value of less than 0.1 up to thick diameter of 360 nm. Finally, PL spectra at 15 K were evaluated. NBE emission and oxygen-related luminescence (3.41 eV) were observed for high height columns [3]. I_{OX} intensity monotonically decreased with decreasing diameter from 260 to 160 nm. Based on these result, the height and the diameter are important parameters to obtain high crystalline GaN nanocolumns.

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Author Index

Bold page numbers indicate presenter