Electronic Materials and Processing
Room: B1 - Session EM-ThA

Quantum Structures and Nitrides Devices
Moderator: F. Ren, University of Florida

2:00pm **EM-ThA1 Filling of Few Electron Quantum Dots Imaged and Characterized By Scanning Force Microscopy**, ***L.P. Cockins***, *Y. Miyahara, S.D. Bennett, A.A. Clerk,* McGill University, Canada, *S. Studenikin, P. Poole, A. Sachrajda,* National Research Council, Canada, *P. Grutter*, McGill University, Canada

The ability of quantum dots to confine single charges at discrete energy levels makes them a promising platform for quantum computation where the intrinsic properties of single electrons, such as spin, act as the conventional 1 and 0 bit in a classical computer. In order to control initialization and to scale up the number of bits, an understanding of both the energy levels of single quantum dots and the variation between dots need to be characterized.

Self assembled quantum dots are of considerable interest in this field because their size, shape, and material can be controlled during the growth process. Controlling these properties is important as these influence the confinement potential, thereby controlling the energy levels of the dot. However, the method of growth makes positioning of the quantum dots difficult and usually they are randomly distributed over the sample surface. This, in addition to the small size of the dot, makes it challenging for lithography techniques to access the quantum dots to perform either charge transport or charge sensing measurements so that the dot properties can be measured.

An atomic force microscope can be used to spatially access the dots, and by applying a voltage between cantilever tip and back-electrode (beneath the dot), the energy levels of individual dots can be probed. At low temperatures the dots are in the Coulomb blockade regime and individual electrons can be controllably added by applying a sufficient bias voltage to overcome this electrostatic repulsive energy. The oscillating cantilever in these experiments is responsible for both loading/emptying the dots through electrical gating and also detecting tunneling events through a change in resonant frequency and/or the amount of energy required to maintain a constant oscillation amplitude. Electrical leads are not required in this experiment which not only leaves the surface electrostatically intact but also gives us the freedom to investigate any dot on the surface.

Using an atomic force microscope we demonstrate the ability to probe the energy levels in few electron self assembled InAs quantum dots. The charging energy, level spacing, and shell structure of single dots are extracted and supported theoretically. Multi-dot complexes are also investigated and pairs of dots which are either capacitively or tunnel coupled are observed. Increasing the oscillation amplitude of the cantilever allows for the additional electron to enter the dot at a higher energy level, in a way probing the excited states of the dot similar to excited state spectroscopy. These findings are also supported by theoretically.

2:20pm **EM-ThA2 InAs Lateral Quantum Dot Molecules with Controllable Configurations**, ***M.K. Yakes***, *A.S. Bracker, C.D. Cress, J.G. Tischler, D. Kim, A. Greilich, D. Gammon, A.R. Laracuente*, Naval Research Laboratory

A quantum dot molecule (QDM) is formed when two or more quantum dots are close enough so that the electronic properties of each dot are affected by the presence of the other. Well controlled, vertically-stacked QDMs are now routinely grown for optical investigations.[1] [#_ftn1] For device applications, laterally coupled dots offer compatibility with existing gate technologies and advantages in scalability. However, growth of complex laterally coupled QDMs is more challenging than the vertically stacked dots.

One method for influencing the lateral position of self-assembled QDs is to introduce features on the substrate which will act as preferred nucleation sites for dot growth.[2] [#_ftn2] One promising technique is to use gallium droplet epitaxy to form a template for further dot growth. In droplet epitaxy, gallium is deposited without arsenic overpressure, forming metallic islands without a wetting layer. When these droplets are exposed to arsenic and annealed they crystallize into homoepitaxial mounds. When InAs is grown on these mounds, the islands appear to grow only on the sloping edges of these mounds. Previous structures grown with this technique have demonstrated flexibility in QDM configuration and excellent uniformity.[3] [#_ftn3]

In this presentation, we will describe new growth techniques that can be used to control the configurations of lateral InAs QDMs. By fixing the direction of the incident indium flux, the indium beam is shadowed by the GaAs mounds, so that InAs dots will only form on the sides of the mound which face the indium source. This allows new configurations of QDMs to be grown that cannot be formed using a rotating substrate. In addition, by capping first layer QDMs with GaAs or AlGaAs and growing additional strain-coupled dots, we demonstrate flexible and uniform three dimensional QDM configurations.

With atomic force microscopy it is not possible to determine the structure of the InAs dots once they are buried under a GaAs capping layer. Cross sectional scanning tunneling microscopy (XSTM) is an ideal technique to examine the final structure with atomic resolution. For bi-molecules, the interdot separation is 8 nm and the center to center distance is 30 nm, which makes them excellent candidates for investigations of electron tunneling using photoluminescence spectroscopy.

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[1] [#_ftnref1] E. Stinaff *et al., Science* **311** 636 (2006)

[2] [#_ftnref2] R. Songmuang *et al., Appl Phys Lett* **82** 2892 (2003)

[3] [#_ftnref3] J.H. Lee *et al., Appl Phys Lett* **89** 202101 (2006)

2:40pm **EM-ThA3 MBE Growth and Optical Properties of GaN Quantum Structures**, ***N. Grandjean***, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland **INVITED**

In this presentation, we will first address the fabrication of III-V nitride based quantum dots (QDs) using molecular beam epitaxy with ammonia as nitrogen source. We will focus on strain-induced Stranski-Krastanov (SK) growth mode in GaN/AlN system and point out the effect of surface free-energy. It is indeed observed that the V/III ratio controls the 3D island formation in a reversible way. In a second part, we will discuss the optical properties of an ensemble of GaN/AlN QDs. Photoluminescence experiments evidence that the transition energies are dominated by a giant quantum confined Stark effect, which results from the presence of a huge built-in electric field of several MV/cm. This electric field is inherent to wurtzite III-nitride based heterostructures when they are grown along a polar axis. It comes from spontaneous and piezoelectric polarization discontinuities arising at interfaces between different materials. Then, mesa are prepared aimed at single dot spectroscopy using micro-photoluminescence. Optical signatures of excitons and bi-excitons are clearly seen on the luminescence spectra. Both positive and negative binding energies are deduced depending on the dot size. A phenomenological model including the built-in electric field present in the dots well accounts for the experimental observations.

3:40pm **EM-ThA6 Growth and Process Technologies for High Efficiency InGaN-Based Light-Emitting Diodes**, ***J.-I. Chyi***, *H.-C. Lin*, National Central University, Taiwan **INVITED**

Raising external quantum efficiency has always been the focused area of research in InGaN blue/green light-emitting diodes (LEDs). In the early 90s, breakthroughs in material growth and p-type doping restored the heat of pursuing high brightness InGaN LEDs. It was, however, several other key technology advancements that made solid-state lighting era a reality. Among these technologies, patterning sapphire substrate and semiconductor surface is one of the most essential one. In this report, we present three different patterning techniques, which emphasize different aspects of patterning technology and show how they impact the external quantum efficiency as well as other characteristics of InGaN/GaN quantum well light-emitting diodes. We report the epitaxial growth of GaN on patterned sapphire substrates (PSSs) with micro-lens of three different geometric shapes by metal-organic chemical vapor deposition. Growth mode analysis shows that micro-lens with sharp tips prohibit the nucleation and growth of GaN on their top and lead to a wider lateral growth region with low dislocation density. The external quantum efficiency (at 20 mA) of LEDs is improved by nearly 20% by using this technique. However, the residual strain instead of dislocation density in the GaN buffer layer plays a heavier role in the external quantum efficiency of the light-emitting diodes. Although the PSS approach has been shown effective and gives the freedom of pattern design, it requires extra photolithographic steps that make it more complicated and costly. We propose a maskless wet-etching method to prepare patterned sapphire substrates, namely naturally etched sapphire substrates (NESSs). At 20 mA, nearly 20% improvement in external quantum efficiency is achieved even the LEDs have already an indium-tin oxide transparent contact layer and a roughened surface. It has also been shown that the uniformity of device performance across the wafer is not a concern when using this technique. The surface patterning techniques reported so far involve spatially with the active region of LEDs and make

the patterning process very critical in maintaining device performance as well as reliability. To avoid this problem, we propose to pattern the dicing streets around the LED chips where no electrical contacts are present. Forming a triangular lattice consisting of dry-etched circular holes with a diameter/periodicity of 3/3 μm on the dicing street. The external quantum efficiency (at 20 mA) of the LEDs is increased by about 13%. Meanwhile, the forward voltage increases only 0.05 V and improved reliability is observed as expected. In addition, a novel growth technique for improving internal quantum efficiency will also be presented. During the growth of quantum wells, a growth interruption is introduced at each InGaN to GaN interface while having trimethylindium (TMIn) and NH3 continue flowing into the reactor. Photoluminescence, X-ray diffraction, atom force microscopy, and high-resolution transmission electron microscopy indicate that the treatment leads to a smoother InGaN surface and InGaN/GaN interface with substantial decrease in V-shape defects density, compared to the samples without the treatment. The external quantum efficiency of 525 nm green LEDs prepared by this process is increased by as much as 43%.

4:40pm **EM-ThA9 ENABLE-Based Growth of In-Rich InGaN for Photovoltaic and Light-Emitting-Diode Devices**, ***T.L. Williamson***, *M.A. Hoffbauer*, Los Alamos National Laboratory, *K.M. Yu, L.A. Reichertz, N. Miller, J.W. Ager, W. Walukiewicz*, Lawrence Berkeley National Lab

A wide range of photovoltaic (PV) and light-emitting-diode (LED) devices can be made utilizing the wide band gap tunability of InxGa1-xN (0.7 eV to 3.4 eV, 1>x>0). Growing In-rich InxGa1-xN films with strong photoluminescence in the green and red portions of the visible spectrum has faced considerable challenges due to In segregation and other materials issues. These challenges have precluded the growth of both compositionally graded InxGa1-xN materials and higher bandgap Ga-rich materials on top of lower bandgap In-rich materials. Overcoming these difficulties has proved formidable for conventional epitaxial techniques due to the low decomposition temperatures of In-rich materials (e.g. InN~550°C) and the required growth temperatures for Ga-rich materials (e.g. GaN >800°C).

Energetic neutral atom beam lithography & epitaxy (ENABLE) is a recently developed low-temperature thin film growth technology developed at LANL that utilizes a collimated beam of energetic neutral N atoms (kinetic energies 0.5 to 5.0 eV) to react with evaporated Ga and In metals to grow InxGa1-xN. ENABLE is similar to MBE, but provides a much larger N atom flux. The high kinetic energy of the reactive N atoms substantially reduces the need for high substrate temperatures, making isothermal growth over the entire InxGa1-xN alloy composition range possible at rates of >3 mm/hr with no toxic precursors or waste products.

Current progress using ENABLE for growing InN, GaN, InxGa1-xN, and graded InxGa1-xN films over the full composition range will be presented including data on film photoluminescence, crystallinity, electrical properties, doping, and electroluminescence. ENABLE-grown InxGa1-xN films show strong photo- and electro-luminescence spanning the entire visible region of the spectrum, with carrier mobilities ranging from ~10 to >1400 cm2/Vsec and background carrier concentrations typically in the low 1017 range. Evidence for p-type doping of In-rich InxGa1-xN films and characterization of p/n junctions will be discussed along with the prospects for using ENABLE to fabricate efficient devices for PV and LED applications.

5:00pm **EM-ThA10 Self-annealing Effect in Neutron-Irradiated AlGaN/GaN High Electron Mobility Transistors**, ***G. Ko***, Korea University, South Korea, *F. Ren, S.J. Pearton*, University of Florida, *J. Kim, H.-Y. Kim*, Korea University, South Korea

AlGaN/GAN High Electron Mobility Transistors (HEMTs) have been studied due to their chemical and physical stability under harsh environments as well as high power and high frequency applications. Especially, AlGaN/GaN HEMT is considered as the potential candidate for space-based systems such as the space shuttles and the satellites. It is empirically known that displacement threshold energy (E_d) which is the energy required to displace an atom from its lattice position is inversely proportional to lattice constants. Since the lattice constant of GaN (a = 3.2496 Å) is smaller than Si (5.4301 Å) or GaAs (5.6533 Å), its radiation hardness is much better than these. Since neutron-induced effects on AlGaN/GaN heterostructures are not well known. We investigated self-annealing effect occurred in low-dose ($< 10^{12}$ cm^{-2}) neutron-irradiated AlGaN/GaN HEMT at room temperature. The device structure consisted of 25 nm AlGaN with 50 nm GaN cap layer on undoped 2 um GaN. These layers were grown on AlN buffer layer and c-plane sapphire by MOCVD. Ohmic metal was Ti/Al/Ni/Au and gate metal was Ni/Au. Neutron irradiation was performed with MC-50 cyclotron at Korea Institute of Radiological and Medical Sciences. Neutrons were generated when 35MeV protons collided with beryllium target occurring nuclear reaction. The average neutron energy was 9.8 MeV and the total fluence was 5.49×10^{11} cm^{-2}. Electrical properties (V_{ds}-I_{ds}, V_{gs}-I_{gs}, and transconductance) had been measured during 30 days after neutron irradiation. We could observe V_{ds}-I_{ds} drastically decrease for 7 days, which meant surface traps and deep traps were created in AlGaN/GaN HEMT. However its current level was gradually recovered after 7 days. And the recovery of transconductance and leakage current were also confirmed. This self-annealing effect can be attributed to the recombination of the created defects because the distance between the neighboring defects is very short. The defect clusters that are mobile at room temperature were created by neutron irradiation. The details about the irradiation and self-annealing will be presented.

5:20pm **EM-ThA11 Engineering Epitaxial AlN Thin Films on Wide Bandgap Semiconductors**, ***Y.-C. Perng***, *J. Chang*, University of California, Los Angeles

Wide bandgap semiconductors have been interesting for high temperatures operation and serving as materials using in high power and RF devices because of their high breakdown voltages. Aluminum nitride, a wide bandgap material (6.2 eV), is a promising interfacial layer or dielectric material on wide bandgap semiconductors, especially SiC and AlxGa1-xN/GaN. Because of its small lattice mismatch to SiC and AlxGa1-xN/GaN (1.3% and <2%)1 and a similar thermal expansion coefficient, it could potentially lower the interface state densities between the materials. Conventionally, AlN thin films are deposited by molecular beam epitaxy (MBE) on these wide bandgap materials. In this work, ALD is chosen to assess its ability to grow ultra-thin, uniform, and conformal AlN on these substrates, as a potential alternative for synthesizing epitaxial materials over a larger substrate and at lower temperatures.

Atomic layer deposition (ALD) has been utilized to synthesize AlN thin films by using trimethyl aluminum (TMA) and ammonia (NH3) as precursors at 400~500oC under high vacuum as 10-4~10-6 torr. The deposition rate of AlN on SiC and AlGaN were determined to be about 0.08nm/cycle. The composition, microstructure, and surface morphology were determined by x-ray photoelectron spectroscopy, transmission electron microscopy, x-ray diffraction and atomic force microscope. Fourier Transform infrared spectroscopy is implemented to study the change of surface functional groups during TMA and ammonia pulses, in an effort to affirm the mechanism leading to the growth of stoichiometric AlN. The as-deposited AlN was amorphous, as monitored by *in situ* by RHEED analysis but can be transformed into an epitaxial layer on SiC and AlGaN by a high temperature rapid thermal annealing process at 900oC. By synchrotron based XRD, we determined the epitaxial relationship between AlN and SiC to be AlN(11-20)||SiC(11-20) and AlN(0004)||SiC(0008). Similarly, the epitaxial relation to AlGaN is AlN(11-20)||AlGaN(11-20) and AlN(0002)||AlGaN(0002). Capacitance-voltage and conductance -voltage characteristics are used to determine the interface states density between the thin film and wide bandgap substrate. This process is also combined with an ALD Al2O3 process to synthesize aluminum oxinitride as a graded interfacial layer between AlN and Al2O3, to realize the fabrication and testing of viable MIS-HEMT structures.

1 H. Morkoc, S. Strite, G. B. Gao et al., Journal Of Applied Physics 76 (3), 1363 (1994).

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