Science of Semiconductor White Light Topical Conference Room 310 - Session WL-MoA

Science of Semiconductor White Lighting

Moderator: K.H.A. Bogart, Sandia National Laboratories

2:00pm **WL-MoA1 Improving the Brightness of GaN-based Light Emitting Diodes in the Green*, C. Wetzel,* *T. Detchprohm,* Rensselaer Polytechnic Institute **INVITED**

Technological innovations to address impeding energy cost raises are of high priority for global economics. Generating white light without the heating losses of light bulbs by means of semiconductor light emitting devices is a prime opportunity to reduce the energy consumption for lighting -- about 20% of the total energy consumption in the US -- by an estimated 28%. Alloys of GaInN offer the prospect for high power light emitters across the entire visible spectrum. While high performance red LEDs have been developed in AlGaInP materials, blue GaInN LEDs have shown major progress in recent years. The immediate challenge is to increase performance throughout the green from 520 nm to 550 nm. Based on detailed spectroscopic bandstructure characterization of GaInN/GaN alloys and quantum wells we have identified materials and device design parameters for high power LED dies emitting in this range. We developed a production scale epitaxial growth process by metal organic vapor phase epitaxy for 525 nm dominant wavelength at typical 1.7 mW at 20 mA in (350 µm)@super 2@ dies. In a (400 µm)@super 2@ design we reach values of 2.5 mW in unencapsulated die. This corresponds to 5.0 mW upon proper encapsulation and 6 to 8 mW for flip-chip processed devices. We provide an analysis of the performance limitations imparting further development towards higher power and higher efficiency devices. Despite respectable performance there is ample of headroom for improvement in the internal light generation efficiency which furthermore can be enhanced by improvements to the light extraction. We present our approach within the framework of significant future energy savings by solid state white light generation.

2:40pm **WL-MoA3 Indium Incorporation Studies for Blue and Green Emitting Multi-Quantum Wells and Light Emitting Diodes*, D.D. Koleske,*** *S.R. Lee, A.J. Fischer, M.H. Crawford, M.E. Coltrin, M.J. Russell, K.C. Cross,* Sandia National Laboratories

While the promise for tuning the bandgap from 0.7 to 6.2 eV in the group III nitride materials system exists, achieving wavelengths greater than 530 nm is difficult due to several factors. These factors include the disparate growth conditions that must be used for In incorporation, especially temperature, and the lattice mismatch between GaN and InGaN alloys, which may induce compositional instability and decrease structural ordering. The issue of In incorporation becomes particularly important for improving light emission for green LEDs, where the internal quantum efficiency is significantly less than for blue LEDs. Currently, we are investigating the growth of InGaN multi-quantum wells (MQWs) with the aim of understanding how the growth conditions influence In incorporation. The MQW structure is analyzed using x-ray diffraction and dynamical diffraction theory is used to determine the In content and quantum well thickness. Photoluminescence and fabrication of simple LEDs were used to characterize the photo- and electro-luminescence properties of the films. We explored two different growth regimes for improving In incorporation into the QWs. The first growth regime involved growing the MQWs with very high growth rates to capture and bury the In before it desorbs. In this fast growth regime, we were able to incorporate up to 18 % In into the MQWs at 770 °C, leading to 470 nm LED emission. A subsequent reduction of the growth temperature to 725 °C produced green LEDs emitting at 510 nm. The second growth regime involves slower growth rates and lower growth temperatures which allows for increased In residence time on the surface, potentially leading to higher In content in the MQWs. Advantages and disadvantages of both growth regimes will be discussed with a focus on identifying the growth regime that enables the highest luminescence efficiency in green MQWs and LEDs

3:00pm **WL-MoA4 Temperature Measurement and Control during Group-III Nitride MOCVD*, J.R. Creighton,*** *D.D. Koleske, C.C. Mitchell, M.J. Russell,* Sandia National Laboratories

Accurate temperature measurement during group-III nitride MOCVD is difficult due to the broad spectral transparency of the substrates and epitaxial layers. In fact, there is no readily available method that measures the true surface temperature during deposition on sapphire substrates. We have developed a pyrometer in our single-wafer research reactor that operates near the high-temperature bandgap of GaN, thus solving the transparency problem once a ~1 micron thick GaN epilayer has been established. The system collects radiation in the near-UV (380-415 nm) and has an effective detection wavelength of ~405 nm. Near 1000°C, the RMS temperature noise of the system is <0.1°C, and at 800°C the RMS temperature noise is <0.5°C. By simultaneously measuring the reflectance, we can also correct for emissivity changes when films of differing optical properties (e.g. AlGaN) are deposited on the GaN template. By employing the virtual interface method, the reflectance measurement can also be used to monitor growth rates and compute optical properties of the thin films. We have recently modified the pyrometer hardware and software to enable measurements in one of our commercial Veeco D-125 multiwafer MOCVD systems. A method of synchronizing and indexing the detection system with the wafer platen was developed so signals only from the desired wafer(s) could be measured, while rejecting thermal emission signals from the platen. The Veeco D-125 also has more limited optical access, in comparison to our research reactor, so the front end collection optics required a redesign and optimization. Despite the losses in optical throughput and duty cycle, we are able to maintain good performance from 750-1100°C. (Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.).

3:20pm **WL-MoA5 Color Conversion in Light Emitting Devices using Nonradiative Energy Transfer*, M. Achermann,*** *M.A. Petruska, S. Kos, D.L. Smith,* Los Alamos National Laboratory*; D.D. Koleske,* Sandia National Laboratories*; V.I. Klimov,* Los Alamos National Laboratory **INVITED**

Using modern colloidal chemistry, semiconductor nanocrystals (NCs) can be fabricated with nearly atomic precision in a wide range of sizes and shapes. NCs exhibit high photoluminescence (PL) quantum yields and narrow size-controlled emission lines, and they can easily be manipulated into various two-dimensional (2D) and 3D assemblies. All of these properties make NCs attractive building blocks for applications in various optical technologies including light-emitting devices. One problem associated with realizing NC-based light emitters is that the electrical injection of carriers into NCs is complicated by the presence of the insulating passivation layer. All previous attempts to electrically contact NCs have utilized hybrid inorganic/organic composites comprising conducting polymers. However, the performance of these devices is severely limited by low carrier mobilities in both NC and polymer components and poor polymer stability with respect to photooxidation. Here, we present an alternative, "noncontact" approach to injecting carriers into NCs via nonradiative energy transfer (ET) from a proximal epitaxial quantum well (QW). Monitoring time and spectrally resolved PL dynamics, we observe an efficient energy outflow from the QW, which is accompanied by a complimentary energy inflow into a dense monolayer of NCs assembled on the top of the QW. The measured ET rates are very fast and should allow for the efficient pumping of NCs not only in the spontaneous but also in the stimulated emission regime.

4:00pm **WL-MoA7 Photonic Crystals for Enhanced Light Extraction in InGaN LEDs*, A.J. Fischer,*** *D.D. Koleske, G.R. Hadley, J.R. Wendt, R.J. Shul,* Sandia National Laboratories*; J.J. Wierer, M.R. Krames,* Lumileds Lighting **INVITED**

In order to realize semiconductor-based white lighting with efficacies of 200 lm/Watt, InGaN light emitting diodes (LEDs) must have wall plug efficiencies on the order of 50% or better. Even when internal quantum efficiencies approach 100%, most LEDs suffer from poor light extraction efficiency. The majority of photons generated inside of a high index semiconductor bounce around due to total internal reflection where they have a high probability of being reabsorbed. Many methods have been used to improve the extraction efficiency of LEDs including chip shaping, surface texturing, and resonant cavity LEDs. Photonic crystals can also be used to enhance extraction efficiency by either suppressing emission of light into waveguiding modes or by extracting waveguiding modes via Bragg scattering. We have fabricated InGaN LEDs with an incorporated photonic lattice by etching holes into the GaN surface. E-beam lithography was used for submicron pattern transfer and Cl-based inductively-coupled plasma reactive ion etching was used to etch holes in GaN. For these LED structures, the photonic lattice improves light extraction by extracting light emitted into waveguiding modes. An overview of light extraction from InGaN LEDs will be given as well as recent device results from InGaN photonic crystal LEDs. Sandia National Labs is a multi program laboratory operated by Sandia Corporation, a Lockheed Martin Company for the

United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

4:40pm **WL-MoA9 CdSe Nanocrystal Light Emitting Diodes: Toward Full Spectrum White Light Generation**, ***A.H. Mueller***, *E.A. Akhadov, M.A. Petruska, M. Achermann, V.I. Klimov, M.A. Hoffbauer,* Los Alamos National Laboratory

Semiconductor nanocrystals (NCs) of CdSe exhibit light emission across the visible light spectrum with optical excitation quantum efficiencies (QE) exceeding 80%. With the emission wavelength determined by the NC size, blends of different size NCs as chromophores can be used to generate a broadband white light spectrum. The ultimate efficiency of such a source will be determined not by the NC's QE, but by the efficiency of the excitation source. Alternatively, direct electrical excitation of NCs can eliminate inefficiencies in photon absorption and re-emission by the chromophore. Previous electrically pumped NC-LEDs used hybrid polymer/NC architectures to achieve direct injection of carriers into the active layer. Efficiency in these devices is limited by the poor carrier mobilities in the organic components, and they exhibit short operative lifetimes due to photooxidation of the injection layers. These barriers to high efficiencies can be removed by combining inorganic, semiconducting injection layers of GaN with NCs, but this combination is difficult to achieve due to the harsh conditions typically needed for GaN film growth. We have succeeded in fabricating NC LEDs by encapsulating single- and multilayers of CdSe/ZnS core/shell NCs in semiconducting GaN thin films. The GaN films are grown using Energetic Neutral Atom Beam Lithography/Epitaxy (ENABLE), a unique thin film growth technique developed at LANL for growing semiconducting nitride films at low temperatures. Layers of NCs were assembled on a p-GaN substrate using Langmuir-Blodgett (LB) techniques and encapsulated with ENABLE grown n-GaN. This structure allows direct injection of carriers into the NCs, resulting in light emission at a wavelength determined by the NC's size. Prototype devices have shown emission from single and multicolor NC layers. Ultimately, assemblies of different size NCs as active regions in these LEDs will permit tailoring their output for generating full spectrum white light

5:00pm **WL-MoA10 Trapped Whispering-Gallery Optical Modes in White Light-Emitting Diode Lamps with Remote Phosphor**, ***H. Luo***, *J.K. Kim, Y.A. Xi, E.F. Schubert,* Rensselaer Polytechnic Institute; *J. Cho, C. Sone, Y. Park,* Samsung Advanced Institute of Technology, South Korea

Phosphorescence efficiency in high-power white light-emitting diode (LED) lamps is investigated by three-dimensional ray tracing. It is shown that the absorption of the phosphorescence by the LED chip is greatly reduced by employing a remote phosphor, resulting in the improvement of lamp efficiency. However, for lamps with remote phosphor, a significant fraction of the phosphorescence is found to be trapped as whispering-gallery modes propagating along the circumference of the encapsulant, which causes significant optical loss. The whispering-gallery modes, which occur irrespective of the shape of the encapsulation dome, are shown to be sensitively dependent on the diffusivity of the reflector cup employed in the lamp. Dichromatic LED lamps with remote phosphor were fabricated for reflector cups with different diffusivity. The phosphorescence efficiency is found to be improved by up to 27% for a remote phosphor configuration and a diffuse reflector cup. The experimental results are consistent with theoretical ray tracing simulations.

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