Plasma Science and Technology Division
Room 104C - Session PS+MN-WeM

IoT Session: Enabling IoT Era

Moderators: Ankur Agarwal, KLA-Tencor, David Lishan, Plasma-Therm LLC

8:00am **PS+MN-WeM-1 A "Moore's Law" for Packaging**, ***Subramanian Iyer***, University of California at Los Angeles **INVITED**

While Silicon has scaled aggressively by over a factor of a few thousand over the last six decades the progress in packaging has been more modest – a linear factor 4-5 in most cases. In this talk, we will examine the reasons for this lag and what we are doing to fix this imbalance. Packaging is undergoing a renaissance where chip-to-chip interconnects can approach the densities of on-chip interconnects. We will discuss the technologies that are making this happen and how these can change our thinking on architecture and future manufacturing. Specifically, we will discuss two embodiments: Silicon as the next generation packaging substrate, and Flexible electronics using fan-out wafer level processing. We will describe how this is needed for the IoT era.

8:40am **PS+MN-WeM-3 Fabrication, Chemical Lift-Off and Optical Characterization of Nanoscale III-Nitride Light Emitters**, ***Lesley Chan***[1], *C Pynn, P Shapturenka, T Margalith, S DenBaars, M Gordon,* University of California at Santa Barbara

High density, near eye, and flexible display technologies of the future will require efficient micro- and nanoscale pixels based on light emitting diodes (LEDs). Liquid-crystal displays (LCD) and organic LEDs are currently used or envisioned for these applications, but their efficiencies and lifetimes are low. Higher efficiency III-nitride materials are promising for such displays, but manufacturing and implementing sub-micron scale InGaN/GaN structures that emit at different wavelengths into devices is currently difficult. Moreover, flexible and curved display applications require substrate thinning or separating individual devices from their growth substrates for subsequent printing or pick-and-place onto alternate substrates.

In this talk, we present an easy and scalable fabrication and chemical lift-off method to create nanoscale InGaN LEDs, along with morphological and optical characterization of the resulting structures using photo- (PL) and cathodoluminescence (CL). Active and sacrificial multi-quantum well (MQW) layers were epitaxially grown on semipolar (20-21) GaN substrates using MOCVD and patterned into large mesas (4x4 mm^2) using photolithography and Cl_2/N_2 plasma etching. Mesas were 'flip-chip' bonded to sapphire and chemically released from the GaN growth substrate by photoelectrochemical (PEC) etching of the sacrificial MQW layer, leaving behind a 1-2 μm thick p-GaN/MQW/n-GaN device layer protected with Si_3N_4. Nano-LEDs (nLEDs) were then patterned on the thin film device layer using colloidal lithography and plasma etching, released using HF vapor, and suspended in water, resulting in a colloidal solution of InGaN nLEDs. LED geometry was tuned by adjusting the SiO_2 colloid mask size (500-2000 nm) and plasma processing, e.g., using an isotropic CF_4/Ar mask reduction etch and vertical GaN etch with Cl_2/N_2. Preliminary PL results show a five-fold increase in emission for on-wafer nLEDs compared to their planar (unpatterned) counterparts. The large PL enhancement is thought to be due to increases in both IQE and EQE resulting from relaxed strain (decreasing the quantum confined Stark effect) and enhanced light extraction from increased scattering and graded index effects (i.e., non-planar geometries), respectively. CL spectroscopy and imaging of individual nLEDs also revealed strong MQW emission after processing with peak wavelengths at 430 nm. This work suggests that the 'flip-chip' approach, combined with colloidal lithography and chemical release, is a viable route to solution processable, high efficiency nanoscale light emitters.

9:00am **PS+MN-WeM-4 High Radical Flux, with Low Ion and Photon Flux, Plasma Source, for MEM'S Technology**, ***Marc Segers***, *Y Pilloux, D Lishan, S FERRAND,* Plasma-Therm LLC

Micro-electromechanical system (MEMS) are main constituent of a variety of sensors, that include pressure and vibration sensors, accelerometers and gyroscopes, and radiation and temperature sensors. MEMS is a technology that could answer the IoT's requirements for sensors high sensitivity.

To be able to produce MEMS with lower cost and higher quality, different steeps are necessary with preventive treatment, like substrate cleaning or sacrificial photoresist removal, with plasma.

In this work, we introduce a unique inductively coupled downstream plasma source configuration to generate high density radical concentration, for a chemical action and surface activation, but without high ion and photon fluxes, in opposition with conventional inductively coupled plasmas.

Our plasma technology provides a unique process capability for ultimate surface preparation, removal of most difficult residues formed during semiconductor and MEMS processing. System features an innovative approach to "Inductive Coupling", introducing a proprietary plasma confinement technology that is capable of a quasi-full gas dissociation inside the discharge tube, at low RF power. Although the plasma discharge tubes are isolated from the treatment chamber, with a remote plasma design, they deliver a large concentration of free radicals. That "High Density Radical Flux" technology (HDRF®) has demonstrated concentration levels up to 1,000 times higher than conventional plasma sources. HDRF® provides a damage free processing, allowing cleaning of high aspect ratio structures, preventing collapsing or stiction free of membranes, and activation of ultra-sensitive materials, that could be find in MEMS technology. Most of applications include Bosch polymer removal, low temperature photoresist stripping, descum and activation of ultrasensitive surfaces prior to bonding, like MEMS capsuling or shielding.

The low ion and photon exposure significantly reduces the opportunity for damage to sensitive layers. This inductive plasma arrangement prevents local heating and charging on the wafer. With that low local electrical potential, the HDRF® is efficient with 3D structures on the wafer (e.g. MEMS and other high AR features) where preventing ion shielding effects is important.

This work will first describe the **HDRF®** source and different advantages for MEMS processing. Second, several applications using the HDRF® technology will be discussed. These applications will include cleaning of 30:1 aspect ratio (AR) silicon vias, removal of sacrificial layers in MEMS structures, low temperature photoresist removal, and surface smoothing of Bosch generated sidewalls using micro-isotropic etching.

9:20am **PS+MN-WeM-5 Use of Plasma in Advanced Packaging**, ***Michael Seddon***, ON Semi **INVITED**

Advanced Packaging is critical for the continually evolving demands of IoT. As additional functionality is added to the final product, and as its form factor is reduced to further promote mobility and compatibility, the semiconductor package has become even more critical in the integration and overall success of the technology. Advanced IoT packaging is required to offer not only the reliably and protection required of the technology, but it needs to offer the solution with the lowest possible power usage, most efficient use of space and footprint, improved thermal performance, while at a low cost to the end customer. This presentation will discuss several uses of plasma in advanced packaging solutions to meet these demands in both improving the overall reliability performance as well as offering new technology solutions.

11:00am **PS+MN-WeM-10 Low Temperature Plasmas in Nanotechnology Applications**, ***Meyya Meyyappan***, NASA Ames Research Center **INVITED**

The versatility and low temperature processing capability has allowed the use of gas discharges in a variety of nanotechnology applications. This talk will provide an overview of our activities on the use of low temperature plasmas in printed electronics and also the growth of nanomaterials and application development. We have developed an atmospheric pressure plasma jet as an alternative to inkjet and aerosol printing to deposit nanomaterials on paper, plastic, metal foils and textiles etc. to enable flexible, printable electronics. This is a single-step process that does not require a follow-on annealing or sintering in order to get consolidated thin films as is customary with other techniques. The surface temperature is in the range of 20-80 deg C depending on the carrier gas used and the morphology of the film can be controlled by varying the carrier gas and other plasma parameters. Examples of printed materials and their applications will be discussed. The talk will also cover growth of vertical graphene or carbon nanowalls using PECVD on various substrates with interesting properties as well as carbon nanofibers for a variety of applications. The author thanks Ram Gandhiraman, Jessica Koehne, Mike Oye, Mehrdad Shaygan, Mark Rummeli and Jeong-soo Lee.

[1] **Coburn & Winters Student Award Finalist**

11:40am **PS+MN-WeM-12 Gas Phase Synthesis of Pure III-V Semiconductor Nanoparticles from Bulk Metals by using Low Temperature Plasma**, ***Necip Berker Uner***, *E Thimsen,* Washington University in St. Louis

III-V semiconductors are an important class of optoelectronic materials with applications that cover a broad range of the spectrum. Nanoparticles of many of the III-V materials, such as GaAs, InP and InSb, have been synthesized successfully with colloidal methods. However, high quality colloidal syntheses of stibnide and nitride nanoparticles haven't been reported yet. In this work, we present a general gas phase synthesis route for pure nanocrystals of GaSb and GaN. The method relies on reacting aerosols of different metals with help of a low temperature plasma (LTP). Aerosols of Ga, Sb and gaseous nitrogen bearing species were used as precursors. First, the aerosols of the constituent metals were generated via evaporation and condensation. Then, these aerosols were sent into a tubular argon LTP reactor, which provides continuous in-flight processing. As demonstrated in a previous study [1], particles vaporize in the LTP, and the resulting vapor may lead to nucleation of new particles or to re-condensation on the remaining clusters. During the synthesis of the III-V nanomaterials, unipolar charging prevents agglomeration, therefore free-standing particles were produced. Synthesized particles were found to be crystalline and they were mixed on an atomic scale. The stoichiometry was adjusted by manipulating input aerosol concentrations and applied plasma power. Materials were characterized *ex-situ* via high resolution transmission electron microscopy, energy dispersive x-ray spectroscopy, electron-energy-loss spectroscopy, x-ray diffraction and inductively-coupled plasma optical emission spectroscopy. The presentation will provide the results obtained through the extensive characterization methods mentioned. Furthermore, capping the synthesized particles with surfactants, effects of post-etching on the material, and photoluminescent properties will be presented. Operation of the aerosol sources and the mechanism leading to the formation of the compound materials will also be discussed.

[1] N. B. Uner and E. Thimsen, "In-Flight Size Focusing of Aerosols by a Low Temperature Plasma," *J. Phys. Chem. C*, vol. 121, no. 23, pp. 12936–12944, Jun. 2017.

12:00pm **PS+MN-WeM-13 Investigation of Fundamental Hydrocarbon Plasma Chemistry for Unraveling Film Deposition Processes on Nanomaterials**, ***Tara Van Surksum***, *E Fisher,* Colorado State University

Nanostructured materials have numerous desirable properties (e.g., electronic, optical, high surface area) making them useful for range of applications (e.g., catalysts, sensors). However, in some cases, mechanical properties of the materials are not well-suited for their intended environment. Plasma processing of nanomaterials presents an ideal route to modify bulk and surface properties and ultimately, fine tune these materials for desired applications. Hydrocarbon plasmas are often employed to deposit amorphous hydrocarbon films and have been utilized in conjunction with nanostructured materials to increase material hardness. To date, however, a lack of understanding of the fundamental interactions between the material and gas-phase hinders material development. Thus, we aim to elucidate how hydrocarbon plasma deposition processes are influenced by substrate morphology and chemistry, and conversely, how the material ultimately influences the gas-phase chemistry of the plasma.

Here, inductively-coupled hydrocarbon plasma systems (e.g., CH_4, C_2H_4) are investigated to elucidate the roles of gas-phase radicals and gas-surface interactions during film growth processes for flat (e.g., glass slides, Si wafers) and nanostructured (e.g., SnO_2, TiO_2, ZnO) substrates. Materials properties are also assessed to determine the influence of the plasma parameters on film quality. X-ray photoelectron spectroscopy confirms the deposition of amorphous hydrocarbon films on all substrates and scanning electron microscopy images show morphological differences between films deposited under different plasma conditions. Raman spectroscopy reveals that plasma processing creates oxygen vacancies in the TiO_2 lattice structure. Additionally, optical emission spectroscopy is utilized to determine relative species' densities and rotational and vibrational temperatures ($T_R$and T_V, respectively) for multiple species (e.g., CH, C_2). In CH_4 plasma systems, T_V(CH) ranges from ~2000 to ~4000 K under most plasma conditions, whereas T_R(CH) generally reaches values ranging from 1800 to 2800 K. Both values appear to correlate with system pressure and applied rf power. In some cases, the nanostructured substrates have a measurable effect on the gas-phase chemistry (e.g., presence of additional gas-phase species, elevated T_R(CH)), whereas in others, the substrate does not appreciably alter the gas-phase of the plasma. Collectively, these data help to unravel these complicated systems by providing valuable insight regarding possible mechanistic phenomena in hydrocarbon plasmas linked to film deposition on materials with complex architectures.

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