

## Electronic Materials and Photonics Division Room A214 - Session EM+2D+AP+NS+PS-TuM

### New Devices and Materials for Electronics and Photonics

**Moderators:** Sean W. King, Intel Corporation, Michelle M. Paquette, University of Missouri-Kansas City

#### 8:00am EM+2D+AP+NS+PS-TuM-1 Performance Modeling and Design for Spintronic Logic and Memory Devices, *Azad Naeemi*, Georgia Institute of Technology

INVITED

As scaling conventional logic and memory devices becomes more and more challenging, there is a global search for novel materials and devices that can augment mainstream technologies used for data storage and processing. To this end, spintronic materials and devices are promising candidates as they provide dense non-volatile storing elements that enable novel computing paradigms such as in memory-computing and neural networks.

This talk will present physical models for various read and write spintronic mechanisms and quantifies the potential performances of Boolean circuits based on various spintronic logic devices. It will be shown that without major breakthroughs such circuits will not be able to compete with their CMOS counterparts. However, novel circuit paradigms that take advantage of the physics of these devices can potentially provide significant benefits. For example, cellular neural networks based on spintronic devices are projected to perform better compared to their analog CMOS implementation.

While spin-transfer-torque random access memory (STT-RAM) is becoming commercially available, it suffers from relatively large switching currents that limits its density and causes reliability challenges. Novel read and write mechanisms such as spin-orbit torque or magneto-electric effects can potentially address or partially mitigate some of these challenges. In this talk, the array-level potential performance of various magnetic memory devices will be quantified and benchmarked.

#### 8:40am EM+2D+AP+NS+PS-TuM-3 High Yield, Low Variability HfO<sub>2</sub> 1T1R Cells Fabricated in 65nm CMOS, *Jubin Hazra, M Liehr, K Beckmann, N Cady*, SUNY Polytechnic Institute

Hafnium Oxide (HfO<sub>2</sub>) based Resistive Random Access Memory (ReRAM) devices are promising candidates for non-volatile memory, having a wide variety of applications in neuromorphic computing, artificial intelligence and future memory solutions. Stochastic conductive filament (CF) generation and rupture processes, however, contribute to high variability resistive switching in these devices. In order to address this issue, an extensive characterization of HfO<sub>2</sub> 1 transistor 1 RRAM (1T1R) cells was performed to investigate switching yield and cell-to-cell variability. 1T1R devices were integrated into a 300mm wafer platform utilizing the IBM 65nm 10LPe process technology, in which the memristor device stack is implemented between the M1 and M2 metallization layers, using a custom designed FEOL compatible process flow. The ReRAM device stack is comprised of a TiN bottom electrode followed by conformal deposition of the HfO<sub>2</sub> switching layer, Ti oxygen scavenging layer and TiN top electrode. The HfO<sub>2</sub> switching layer was deposited using an atomic layer deposition (ALD) process with an organic precursor. For statistical significance, the performance of 50 different 1T1R cells was compared for cell-to-cell variability in operating voltage and resistance in the on and off state. An impressive 100% switching yield and low cell-to-cell switching variability were observed for these devices. 1T1R cells were also investigated for long term endurance and high temperature retention, exhibiting excellent endurance of up to 1 billion switching cycles with an average  $R_{off}/R_{on}$  ratio of 10:1. As compared to 1T1R cells that we have fabricated with alternative ALD precursors/methods, these devices show superior yield and performance. We are currently performing compositional and structural comparisons between these sets of devices, to elucidate the impact of ALD precursor choice and processing methods on yield and electrical performance.

#### 9:00am EM+2D+AP+NS+PS-TuM-4 Heat Transfer Proximity Effects in Resistive Memory Crossbar Arrays, *Marius Orlowski, M Al-Mamun*, Virginia Tech

Evidence for thermal cross talk in resistive RAM memory arrays is presented. Frequent switching of a resistive memory cell (Cu/TaO<sub>x</sub>/Pt) may lead to a considerable local accumulation of Joules heat. The heat generated in a stressed device spreads via common electrode lines to the

neighboring cells impacting their switching behavior. As a probe into degraded performance of the neighbor cells we choose the cell itself set into the on-state under specific conditions. The cell is set at a critical compliance current  $I_{cc}$  that allows repeated switching for no more than  $\sim 15$  cycles. After the maximum number of cycles the on-state becomes volatile. For a lower  $I_{cc}$ , the cell produces a volatile on-state, and for higher  $I_{cc}$  the cell switches for hundred of times with a stable on-state. We find that the cells in close proximity of the heated device display various degrees of degradation indicated by a reduced number of cycles of the probed cell. The 1<sup>st</sup> neighbor cell experiences the greatest, and the 4<sup>th</sup> neighbor cell the smallest degradation. This indicates the spread of the heat from the heated device to its neighbors. After a sufficient cooling off period (10 minutes or longer), all the neighboring cells and the heated device display again the maximum number of cycles i.e. 15, when set under the critical compliance current and reset, repeatedly. Also cells that don't share any of the common electrode metal lines with the heated source cell, may degrade provided that the intermediate cells are set to on-state, thus enabling a continuous thermal conduction path between the heated cell and the probed cell. The heat dissipation from the heated device is slower for narrow and thin metal electrode lines than for wide and thick metal lines. However, in case of wide and thick metal lines more distant neighbor cells are affected by the parasitic cell-to-cell heat transfer.

We have performed the characterization of the neighboring cells along the Cu and Pt electrode lines. We find that the performance degradation of the neighboring cells along the Cu line is significantly stronger than along the Pt metal line. This observation is consistent with the much better heat conductivity of Cu lines (385W/(mK) and 150nm thick) than the Pt (72W/(mK) and 50nm thick) lines, but is at odds with the assumption of the standard electro-chemical metallization model postulating a conical shape of the Cu filament with a broad base of the cone at the Pt electrode and a tip at the Cu electrode. We discuss the extant controversial experimental evidence and models for the filament's shape and propose an hour-glass shape for the filament reconciling the extant findings and our thermal results.

#### 9:20am EM+2D+AP+NS+PS-TuM-5 High Performance Memristive Action in Methylammonium Bismuth Iodide ([MA]3BiI<sub>9</sub>) Films, *P Cheng*, Vanderbilt University; *G Luo*, Washington University in St. Louis; *Z Gao*, University of Central Florida; *A Thind*, *R Mishra*, Washington University in St. Louis; *Parag Banerjee*, University of Central Florida

We demonstrate high performance (ON/OFF  $\sim 2.4 \times 10^5$ ) resistive switching in methylammonium bismuth iodide ((CH<sub>3</sub>NH<sub>3</sub>)<sub>3</sub>BiI<sub>9</sub> or, MBI) thin films.<sup>1</sup> MBI has a post-perovskite structure and consists of 2D layers of face-shared

BiI<sub>6</sub> octahedra. This talk focuses on the structure, composition and associated defect chemistry that is critical for memristive behavior in MBI films.

Memristors are formed by contacting MBI films with aluminum electrodes. The switching for a 200 nm film is observed at voltages  $\sim 0.5$  V. High frequency performance of these memristors shows a peak ON/OFF ratio  $2.4 \times 10^5$  at 50 KHz. The ON state retention is maintained at 50C for  $> 10^6$  seconds. Stable room temperature endurance is noted for up to 1000 cycles. Energy dispersive x-ray spectroscopy on planar memristor devices show that, postswitching,

a detectable change in the I- concentration is observed closer to the anode side. Density-functional theory (DFT) calculations show low activation barrier for iodine migration in agreement with the experimental results. The DFT calculations also provide insights about the migration pathway and strategies to control this behavior.

From a synthesis perspective, MBI films can be deposited using solution as well as low temperature ( $< 200C$ ), atmospheric CVD technique.<sup>2</sup> The compounds are air stable. This family of ternary compounds offers a large compositional and structural tunability; unlike binary metal oxides commonly used for memristors. As opposed to recent 2D MoS<sub>2</sub> based planar, tunneling RAM devices<sup>3</sup>, the vertical stack of the 2-terminal memristor bodes well for scalability. Thus, we propose that hybrid organic-inorganic thin films may offer strategic materials and design advantages together with seamless process integration into current Si-based devices.

References:

1. Cheng, P., Thind, A., Gao, Z., Luo, G., Mishra, R., Banerjee, P., "High performance memristors from methylammonium bismuth iodide thin films", Submitted.

# Tuesday Morning, October 22, 2019

2. Chen, X.; Myung, Y.; Thind, A. S.; Gao, Z.; Yin, B.; Shen, M.; Cho, S. B.; Cheng, P.; Sadtler, B.; Mishra, R.; Banerjee, P., "Atmospheric pressure chemical vapor deposition of methylammonium bismuth iodide thin films", *J. Mater. Chem. A*, 2017, 5, 24728 - 24739.

3. Vu et al., "Two-terminal floating-gate memory with van der Waals heterostructures for ultrahigh on/off ratio", *Nat. Comm.*, 2016, DOI: 10.1038/ncomms12725.

9:40am **EM+2D+AP+NS+PS-TuM-6 Mechanism of Chalcogen Passivation of GaAs Surfaces, Takayuki Suga, S Goto**, UEC-Tokyo, Japan; *A Ohtake*, NIMS, Japan; *J Nakamura*, UEC-Tokyo, Japan

GaAs surfaces are stabilized by surface treatments with Se or S through the reduction of the dangling bond density [1,2]. It has long been thought that the Se- or S-treated GaAs(111)B-(1x1) surface has a simple structure; the outermost As atoms of the ideal (111)B surface are completely replaced by Se or S atoms, the Se- or S-terminated model [3]. In general, the structural stability of compound semiconductor surfaces can be explained in terms of the so-called electron-counting rule (ECR) [4]. The Se- or S-terminated model, however does not satisfy ECR. Recently, the atomic structure of the Se-treated GaAs(111)B surface has been revisited [5] and another structure model has been proposed, where the Se atoms substitute 3/4 of the topmost surface As atoms in a (2x2) unit [6]. This mixed Se/As-terminated model satisfies ECR, being electronically stable [6]. We have depicted phase diagrams of Se- or S- treated GaAs(111)B surface at 0K as functions of the chemical potentials of Se ( $\Delta\mu_{\text{Se(S)}}$ ) and As ( $\Delta\mu_{\text{As}}$ ). The (2x2) As-trimer and the mixed Se(S)/As-terminated surfaces appear under Se poor condition. It is noted that the Se- or S-terminated surface also becomes stable as  $\Delta\mu_{\text{Se}}$  or  $\Delta\mu_{\text{S}}$  increases, respectively, even though these surfaces are not qualified for ECR.

The Se(S)-treated GaAs(111)B surface is prepared experimentally by molecular beam epitaxy under a finite temperature and a gas pressure. Therefore, it is necessary to consider the free energy of a molecule in vapor phase. In this study, we investigate the stabilization of the Se- or S-treated GaAs(111)B surface structures by considering the beam equivalent pressure of As and Se(S) in a growth temperature using the first-principles calculations within the density functional theory. The chemical potentials of molecules are derived from the partition functions for the translation, the rotation, and the vibrational motions.

In the phase diagram for the actual experiment condition,  $T=800\text{K}$ , the mixed Se/As terminated surface appears in the Se pressure of  $10^{-15}$ - $10^{-5}$  Torr, being consistent with the recent experiment [5]. Surprisingly, the Se-terminated surface also becomes stable as the Se pressure increases. We will discuss the stabilization mechanism of the chalcogen-treated GaAs surfaces.

[1]J. Fan, H. Oigawa and Y. Nannichi, *Jpn. J. Appl. Phys.* **27**, L2125 (1998).

[2]T. Scimeca, Y. Watanabe, R. Berrigan, and M. Oshima, *Phys. Rev. B* **46**, 10201 (1992).

[3]V. N. Bessolov and M.V. Lebedev, *Semiconductors* **32**, 11 (1998).

[4]M.D. Pashley, *Phys. Rev. B* **40**, 10481 (1989).

[5]A. Ohtake and Y. Sakuma, *Cryst. Growth Des.* **17**, 363 (2017).

[6]A. Ohtake, S. Goto and J. Nakamura, *Sci. Rep.* **8**, 1220 (2018).

11:00am **EM+2D+AP+NS+PS-TuM-10 Combining 2D and 1D Atomic Scale Tailored Nanowire Surfaces for Novel Electronics and Photonics, Anders Mikkelsen**, Lund University, Sweden **INVITED**

The III-V nanowire (NW) technology platform has reached a level of advancement that allows atomic scale control of crystal structure and surface morphology as well as flexible device integration. In particular, controlled axial stacking of Wurtzite (Wz) and Zincblende (Zb) crystal phases is uniquely possible in the NWs. We explore how this can be used to affect electronic, optical and surface chemistry with atomic scale precision opening up for 1D, 2D and 3D structures with designed local properties.

We have previously demonstrated atomically resolved Scanning Tunneling Microscopy/Spectroscopy (STM/S) on a wide variety of these III-V NWs and on operational NW devices[1-4]. We now use these methods for studying atomic scale crystal phase changes, the impact on local electronic properties and demonstrating full atomic resolution STM during device operation[5-7]. We explore the surface alloying of Sb into GaAs NWs with controlled axial stacking of Wz and Zb crystal phases[5] demonstrating a simple processing-free route to 1D and 2D compositional control at the monolayer level. Further we show how Bi can form unique 1D and 2D structures in particular on the unique Wz GaAs NW segments. Using 5K STM/S we measure local density of states of Zb crystal segments in Wz InAs

NWs down to the smallest possible atomic scale crystal lattice change [6], which is effectively a small 2D material segment in a 1D structure. We find that the general Zb electronic structure is preserved locally in even the smallest segments and signatures of confined states in them.

Characterization to the atomic scale during electrical and optical operation is necessary to understand and develop the functionality of structures as discussed above. We demonstrate a novel device platform allowing STM/S with atomic scale resolution across a III-V NW device simultaneously with full electrical operation and high temperature processing in reactive gases[7]. Using 5-15 femtosecond laser pulses combined with PhotoEmission Electron Microscopy (PEEM) we explore local dynamic response of carriers in the 1D Wz and Zb crystal phases down to a few femtoseconds temporally and a few tens of nanometer spatially[8].

[1] E. Hilner et al., *Nano Lett.*, **8** (2008) 3978; M. Hjort et al., *ACS Nano* **6** (2012) 9679

[2] M. Hjort et al., *Nano Lett.*, **13** (2013) 4492; M. Hjort et al., *ACS Nano*, **8** (2014) 12346

[3] J.L. Webb, et al *Nano Lett.* **15** (2015) 4865

[4] O. Persson et al., *Nano Lett.* **15** (2015) 3684

[5] M. Hjort et al *Nano Lett.*, **17** (2017) 3634

[6] J.V. Knutsson et al *ACS Nano*, **11** (2017) 10519

[7] J.L. Webb et al, *Sci. Rep.* **7** (2017) 12790

[8] E. Mårzell et al, *Nano Lett.* **18** (2018) 907

11:40am **EM+2D+AP+NS+PS-TuM-12 Nanoflower Decorated GaN and AlGaIn/GaN based Catalyst-free CO Sensors, Monu Mishra, G Gupta**, National Physical Laboratory, India

III-Nitride semiconductors owing unique material properties have proven their potential in the detection of light, chemical, biomolecules and toxic/explosive gases. Despite of numerous advantages viz. biocompatibility, high temperature/frequency tolerance and harsh/adverse environmental condition sustainability, the use of expensive catalysts (e.g. platinum) and higher operation temperature ( $>250^\circ\text{C}$ ) for gas sensing has plagued the development of GaN based cost-effective sensing technology. Up to the best of our knowledge, literature lacks any scientific report on the development of catalyst-free CO sensors operating at room-temperature using GaN or AlGaIn/GaN structures indicating the necessity of dedicated scientific attention in this area. Therefore, we report the fabrication of nanoflowers-decorated GaN and AlGaIn/GaN heterostructure based catalyst-free CO sensors operating at lower (including room) temperature. Planar as well as nanostructured GaN & AlGaIn/GaN thin films were employed for sensors fabrication which exhibited significant CO sensing associated with its superior surface and interface properties. For in-depth understanding, the obtained results were thoroughly analyzed and correlated to investigate the underlying science/phenomenon which revealed that CO sensing on GaN (and AlGaIn/GaN) is governed by the chemical nature of ambient-oxidation induced amorphous oxide ( $\text{O}_2$ ,  $\text{O}^{2-}$  or  $\text{OH}^-$  species) layer grown on the surface and acting as a donor/acceptor state. Besides, electron accumulation at AlGaIn/GaN interface influenced the critical parameters like schottky barrier height, ideality factor etc. perturbed the effective carrier transport and ultimately the device performance. The study demonstrate that development of catalyst-free room temperature operating GaN based CO sensors is feasible using nanostructured surfaces, though further research is required for optimization of device performance.

12:00pm **EM+2D+AP+NS+PS-TuM-13 Surface Transfer Doping of Diamond by Complex Metal Oxides for Power Electronics: A Combined Experimental and Simulation Study, Vihar Georgiev, D Moran, J McGhee**, University of Glasgow, UK

Diamond has unique properties that make it an attractive wide band-gap material to produce future high-performance electronic devices. With a wide band-gap of 5.5eV, a thermal conductivity 5 times greater than 4H-SiC, a high breakdown field and high hole and electron carrier velocities, diamond is a clear stand out candidate for high frequency and high power devices. However, the lack of a suitable doping mechanism has hindered the application of diamond in electronic devices. Conventional substitutional doping techniques are limited as it is difficult to substitute atoms into the diamond crystal lattice.

Surface Transfer Doping (STD) gives the use of diamond for such applications more promise. For STD to occur there are typically two prerequisites: hydrogen terminated diamond (H-diamond) and an electron accepting material in intimate contact with the H-diamond surface. The

# Tuesday Morning, October 22, 2019

hydrogen termination gives the diamond a negative electron affinity which facilitates the transfer of electrons from the diamond to the electron-accepting material, creating a shallow, quasi two-dimensional hole gas (2DHG) in the diamond. This doping process traditionally relies upon interfacial electron transfer between the diamond valence band and favourable energy states provided by atmospheric molecules dissolved in a water layer naturally adsorbed on the diamond surface. However, the stability of this atmospheric layer, upon which the transfer doping process relies, has been a significant limiting factor in the production of high-power handling and robust operation devices.

One of the materials that can improve the performance and stability of STD in diamond are the metal oxides such as  $\text{MoO}_3$  which acts as an alternative electron acceptor medium on the H-diamond surface. In order to validate and understand the physical and the chemical process in such STD, in this work we have combined experimental and simulation studies. The electrical characterisation is done by high temperature Hall measurements. Those experimental results are compared to numerical simulation based on the first principle methods such as Density Functional Theory. Comparing the simulation and experimental results revealed that the electrons are transferred from the diamond to the metal oxides, leading to formation of a sub-surface 2DHG in the diamond. Due to this transfer of electrons to the oxide the hole carrier concentration increases in comparison to the air-exposed H-diamond. Our work shows the potential to improve the stability and performance of hydrogen-terminated diamond electronics devices through incorporation of high electron affinity transition metal oxides.

## Author Index

**Bold page numbers indicate presenter**

— A —

Al-Mamun, M: EM+2D+AP+NS+PS-TuM-4, **1**

— B —

Banerjee, P: EM+2D+AP+NS+PS-TuM-5, **1**

Beckmann, K: EM+2D+AP+NS+PS-TuM-3, **1**

— C —

Cady, N: EM+2D+AP+NS+PS-TuM-3, **1**

Cheng, P: EM+2D+AP+NS+PS-TuM-5, **1**

— G —

Gao, Z: EM+2D+AP+NS+PS-TuM-5, **1**

Georgiev, V: EM+2D+AP+NS+PS-TuM-13, **2**

Goto, S: EM+2D+AP+NS+PS-TuM-6, **2**

Gupta, G: EM+2D+AP+NS+PS-TuM-12, **2**

— H —

Hazra, J: EM+2D+AP+NS+PS-TuM-3, **1**

— L —

Liehr, M: EM+2D+AP+NS+PS-TuM-3, **1**

Luo, G: EM+2D+AP+NS+PS-TuM-5, **1**

— M —

McGhee, J: EM+2D+AP+NS+PS-TuM-13, **2**

Mikkelsen, A: EM+2D+AP+NS+PS-TuM-10, **2**

Mishra, M: EM+2D+AP+NS+PS-TuM-12, **2**

Mishra, R: EM+2D+AP+NS+PS-TuM-5, **1**

Moran, D: EM+2D+AP+NS+PS-TuM-13, **2**

— N —

Naeemi, A: EM+2D+AP+NS+PS-TuM-1, **1**

Nakamura, J: EM+2D+AP+NS+PS-TuM-6, **2**

— O —

Ohtake, A: EM+2D+AP+NS+PS-TuM-6, **2**

Orlowski, M: EM+2D+AP+NS+PS-TuM-4, **1**

— S —

Suga, T: EM+2D+AP+NS+PS-TuM-6, **2**

— T —

Thind, A: EM+2D+AP+NS+PS-TuM-5, **1**