Electronic Materials and Photonics Division
Room B116 - Session EM-WeA

Advanced Materials for Electronic and Photonic Applications

Moderators: Parag Banerjee, University of Central Florida, **Jason Kawasaki**, University of Wisconsin - Madison, **Stephen McDonnell**, University of Virginia

2:20pm **EM-WeA-1 Mind the Gap: Integrating Materials and Engineering Research to Enable Advanced Electronics*, Paul Lane,*** National Science Foundation **INVITED**

Continued advances in computing, communications, and energy technologies present tremendous challenges and opportunities. Underpinning developments have often progressed independent of the intended embodiment, delaying incorporation into next-generation technologies. This presentation will present a broad overview of NSF efforts to address challenges involved with integrating materials research with technological advances, focusing on semiconductors. Research is supported at the level of individual investigators and small teams through topical materials and engineering research programs and at a larger scale through centers and facilities. I will emphasize cross-directorate programs that play a critical role in these efforts, such as Designing Materials to Revolutionize and Engineer Our Future (DMREF), Future of Semiconductors (FuSE), and Future Manufacturing.

3:00pm **EM-WeA-3 Atomic Layer Deposition Defect Engineering of Step Tunneling MIIM Diodes*, Shane Witsell,*** *J. Conley,* Oregon State University

Asymmetric electrode metal/insulator/metal (MIM) tunnel diodes can perform as ultra-fast rectifiers for applications in THz energy harvesting and IR detection, but require low turn on voltage (V_{ON}) and low zero bias resistance (ZBR) as well as current-voltage asymmetry (f_{asym}) and non-linearity (f_{NL}). Combining bilayer insulators as tunnel barriers (MIIM diodes) can improve performance over conventional MIM diodes via asymmetric resonant tunneling or "step" tunneling [1]. Utilizing insulating materials with *intrinsic* defects can further improve η_{asym} and f_{NL} as defect levels in the smaller band gap insulator can provide additional conduction pathways [2]. Finally, it has also been demonstrated that intentionally introduced *extrinsic* defect levels, precisely introduced into the insulator using atomic layer deposition (ALD) [3] can be used to engineer MIM diode performance. In this work, we investigate the use of ALD to intentionally introduce impurity defect levels into the large bandgap insulator of dual insulator MIIM diodes.

Three Al/HfO_2/Al_2O_3/Pt MIIM diodes were investigated: (i) Ti doped: in which a two ALD cycle Ti defect layer was positioned within the middle of the Al_2O_3, and (ii) Ni doped: in which a two ALD cycle Ni defect layer was also positioned within the middle of the Al_2O_3, and (iii) an undoped control. ALD of HfO_2, Al_2O_3, NiO, and Ti_2O_5 was performed using TEMAHf/H_2O,TMA/H_2O, Ni(tBu$_2$DAD)$_2$/O_3, and TTIP/H_2O. For all devices, ALD was performed onto a bottom Pt electrode. After ALD, Al was e-beam evaporated through a shadow mask with 250 µm diameter holes to form top electrodes.

The Ni doped diodes were found to have improved maximum f_{asym} over the undoped control, but increased V_{ON}, likely due to suppression of conduction by to negative charge trapped at Ni defect levels lying energetically near or below the equilibrium Fermi level ($E_{F,equil}$) [4]. The Ti doped diodes showed slightly reduced leakage current, likely due to positive trapped charge in Ti defect levels near or above the $E_{F,equil}$, and also increased maximum f_{asym}. However V_{ON} was not reduced. Compared to the undoped control, introducing either Ni or Ti defect levels resulted in an increase in f_{asym} at higher fields, but a slight decrease at low fields due to charge induced band bending. Ni doped devices also demonstrated a slight increase in breakdown field strength. Additional results will be presented at the meeting including capacitance-voltage measurements. This work shows that ALD can be an effective tool for engineering device behavior.

1. Alimardani et al. Appl. Phys. Lett.**102,** 143501 (2013)
2. Alimardani et al. Appl. Phys. Lett. **105**, 082902 (2014).
3. Holden et al. J. Appl. Phys. **129**,144502 (2021).
4. Ichimura, *J. Electron. Mat.* 48, 583 (2019).

3:20pm **EM-WeA-4 Silicon-Doped Titanium Nitride with Near-Zero Temperature Coefficient of Resistivity (0.05 ppm/K) in the Temperature Range, 80 K - 420 K*, S. Novia Berriel,*** *C. Feit,* University of Central Florida*; M. Islam,* University of Virginia*; J. Shi,* University of Central Florida*; A. Dhamdhere, H. Kim,* Eugenus, Inc.*; P. Hopkins,* University of Virginia*; D. Le, T. Rahman, P. Banerjee,* University of Central Florida

We demonstrate a materials system where the temperature coefficient of resistivity (TCR) can be effectively “dialed” to near zero (~ 0.05 ppm/K) across a wide temperature range spanning from 80 K to 420 K. Materials that show this behavior are referred to as near-zero temperature coefficient of resistivity (nz-TCR) materials. nz-TCR materials are instrumental for applications such as wearable strain sensors, automobile electronics, and microelectronics.

Our strategy to achieve nz-TCR is to atomically combine materials of opposing TCR’s. Metals exhibit positive TCR, while semiconductors and insulators exhibit negative TCR. Atomic layer deposition (ALD) is well-suited for the task of tuning composition between metallic and insulating phases. To this end, we fabricate $Ti_{100-x}Si_xN$ thin films *via* ALD where the TiN (metal) and Si_3N_4 (insulating) are varied systematically across various sample sets. The TCR accordingly varies from positive (metallic and TiN rich) to negative (insulating and Si_3N_4 rich).

$Ti_xSi_{100-x}N$ films are deposited on a Eugenus® 300 mm commercial QXP mini-batch system. The ratio of precursor pulses are varied from $TiCl_4$ and dicholorosilane (DCS), with NH_3 as a co-reactant as described in our previous work[1]. Specifically, Si content is varied for this work between $2.0 \leq x \leq 3.9$ at%. All $Ti_{100-x}Si_xN$ films are ~ 140 nm thick. The films are investigated *via* temperature-dependent van der Pauw and temperature-dependent Hall measurements, thermal conductivity measurements, x-ray diffraction, x-ray photoelectron spectroscopy, high-resolution transmission electron microscopy combined with electron energy loss spectroscopy.

Our results indicate the films are nanocrystalline in nature with Si segregating at the grain boundaries. The Si appears to “getter” residual oxygen. Supported by density functional theory (DFT) calculations, we show a loss in electron mean free path upon Si addition to TiN. The electron mean free path is approximately ~ lattice parameter for TiN thus, satisfying the Mooij rule[2] – a universal basic criteria for establish nz-TCR behavior in materials.

1.C. Feit, S. Chugh, A. R. Dhamdhere, H. Y. Kim, S. Dabas, S. J. Rathi, N. Mukherjee and P. Banerjee, Journal of Vacuum Science & Technology A 38, 062404 (2020).

2.J. H. Mooij, physica status solidi (a) 17, 521-530 (1973).

4:20pm **EM-WeA-7 An Auric Goldfinger Inspired Search for Copper Replacement Conductors*, Sean King,*** Intel Corporation **INVITED**

In the spy film “Goldfinger”, MI6 agent James Bond’s nemesis Auric Goldfinger plotted to corner the world gold market by radioactively contaminating Fort Knox’s gold bullion supply. This presentation will examine the inverse scenario where present-day geopolitical tensions and supply chain constraints have the potential to limit the semiconductor industry’s ability to implement platinum group metals as potential copper conductor replacements. We will begin by first describing the interconnect resistivity scaling challenges that motivate the consideration of non-copper conductors and how certain platinum group metals offer the potential to outperform copper at nanometer wire dimensions (specifically Ruthenium, Iridium, and Rhodium). To further motivate consideration of platinum group metal conductors, we share a benchmarking Meta-analysis of thin film and nanowire resistivities reported in the scientific literature for these metals along with numerous other metals also in consideration (i.e. Cobalt, Tungsten, Molybdenum). We will conclude by examining the supply chain challenges that may ultimately play a role in the selection of future copper replacement conductors and discuss research needed to address these challenges.

5:00pm **EM-WeA-9 Chalcogenide p-Type Transparent Conductors*, Andriy Zakutayev,*** 15013 Denver W pkwy **INVITED**

Transparent conductors (TCs) are unusual materials that are optically transparent to visible light like insulating glass yet have electrical conductivity like opaque metals. The TCs are useful for a broad range of applications including flat panel displays, light-emitting diodes, solar cells, Particularly rare but useful for optoelectronic energy conversion devices are transparent materials that have p-type electrical conductivity with holes rather than electrons (n-type) as majority charge carriers. In contrast to n-type TCs that are usually oxides, some of the top performing p-type TCs are nitrides (e.g. Mg:GaN) or chalcogenides (i.e. sulfides, selenides, tellurides).

In this presentation, I will focus on wide band gap chalcogenide materials as p-type transparent conductors for photovoltaic and photoelectrochemical solar cells. First, I will give an overview desired physical properties of TCs besides transparency and conductivity, and present high-throughput research workshop that can be used to experimentally and theoretically screen candidate materials for TC applications [1]. Then I will give two examples of how these design principles and research methods can be used to synthesize and characterize Zn1-xCuxS [2] and ZnTe1-xSex [3] chalcogenide p-type transparent conductors, and integrate them in CdTe thin film photovoltaic devices [4].

[1] Chem. Rev. 2020, 120, 4007; [2] Matter 1 862 (2019); [3] J. Mater. Chem. C, 10, 15806 (2022); [4] ACS Applied Energy Materials 3 5427 (2020)

5:40pm **EM-WeA-11 Strain Manipulation of Ferroelectricity and Flexoelectricity*, Harold Hwang,*** Stanford University and SLAC National Accelerator Laboratory **INVITED**

The ability to create and manipulate materials in two-dimensional form has repeatedly had transformative impact on science and technology. We have developed a general method to create freestanding complex oxide membranes and heterostructures using epitaxial water-soluble buffer layers, with millimeter-scale lateral dimensions and nanometer-scale thickness. This facilitates many new opportunities we are beginning to explore; here we will focus on the use of tensile strain and strain gradients to control the ferroelectric and flexoelectric response of oxide membranes.

Author Index

Bold page numbers indicate presenter