2D Materials

Room 122 - Session 2D-WeA

2D Materials: Sensors and Devices

Moderators: Vikram Deshpande, University of Utah, **Andrey Turchanin**, University of Jena

2:15pm **2D-WeA-1 Electric-Field-Sensitive Polymer Electrolytes for Non-Volatile Doping of Two-Dimensional Field-Effect Transistors**, ***Susan Fullerton Shirey***, *D. Sarawate, P. Prem,* University of Pittsburgh*; K. Xu,* Rochester Institute of Technology*; E. Beckman,* University of Pittsburgh **INVITED**

Solid polymer electrolyte gating provides access to regimes of transport in two-dimensional (2D) materials that would otherwise be inaccessible using conventional gate dielectrics. The enabling mechanism is the formation of an electric double layer (EDL) at the electrolyte/2D material interface that creates large fields (~V/nm) and therefore induces large p- and n-type carrier densities in 2D materials (~10^{13}-10^{14} cm^{-2}). In this work, we demonstrate a new type of solid polymer electrolyte wherein the electric field created by the ions serves a dual purpose: driving ions to the channel surface to induce heavy doping, and driving chemical reactions that "lock down" the ions at the interface, thereby providing channel doping that persists even after the gate bias is removed (i.e., non-volatile doping). Specifically, the polyethylene oxide (PEO)-based co-polymer is designed with field-sensitive reactive groups to crosslink the polymer and therefore arrest ion mobility, disallowing the ions from diffusing away from the channel surface once the gate is grounded. We demonstrate the non-volatile doping of graphene FETs by applying positive programing gate voltages ($V_G \geq +2$ V), and then monitoring the Dirac point shift and change in ON/OFF current. The non-volatile doping density is ~4 x 10^{12} cm^{-2}, estimated by shifts in the Dirac point, which is more than ten times greater than the intrinsic carrier density. Sheet carrier densities measured by Hall effect and chemical/physical characterization of the polymer electrolyte will be presented. The work is supported by the National Science Foundation (NSF, U.S.) under Grant No. ECCS-EPMD-2132006

2:45pm **2D-WeA-3 Systematic Identification of the Optical Characterization of Hexagonal Boron Nitride Thickness on 300-nm Oxide Substrate**, ***Emily Frederick***, *K. Lina,* University of Central Florida*; M. Lodge,* Truventic LLC*; M. Ishigami,* University of Central Florida

This work presents a systematic process to identify the thickness of a hexagonal boron nitride (hBN) flake on 300-nm silicon oxide substrate through optical microscopy data. HBN exhibits periodic optical variations for thickness levels making it difficult for precise thickness determination, necessitating use of other means to accurately determine thickness. Determining the thickness of hBN under optical microscopy integrated with machine learning could significantly reduce the time intensive task of locating and identifying useful flakes alongside reducing potential misidentification of ideal or nonideal flakes. We assigned specific standard red, green, blue color values to theoretical thickness values and incorporated the shadow of the flakes to further distinguish the flake's thickness. By creating a systematic annotation technique, we aim to have a more efficient method for determining flake thickness for all 2D materials to better incorporate machine learning processes.

3:00pm **2D-WeA-4 Selective Etching of Hexagonal Boron Nitride Under Graphene Stack Using Sulfur Hexafluoride Gas in Different Pressure to Create Two-Dimentional Material Devices**, ***Swastik Ballav***, *R. Tsuchikawa, R. Ben Khallouq, D. Castro,* University of Central Florida*; M. Lodge,* Truventic*; M. Ishigami,* University of Central Florida

Abstract : Recently, twisted bilayer materials fabricated from two-dimensional (2D) materials have been shown to possess unique electronic and optoelectronic properties.Among these, magic angle graphene sandwiched between hexagonal boron nitride (h-BN) has seen significant interests due to its exotic superconducting properties. Sulfur hexafluoride (SF_6) gas commonly utilized for its selective h-BN etching, while it stops at graphene to form electronic contact to these devices.

We will discuss the sensitivity of etching parameters for selective etching of h-BN.Specifically, we measured selective etching of h-BN using SF_6as a function of varying pressure from 10 to 80 mTorr in helium environment at 30°C temperature. At higher pressures, graphene acts as an etch stop and leaves underlying h-BN unetched, which can be exploited to make a via for contacts through insulating h-BN. Such pressure-tunable etch selectivity can create unique device structures such as a suspended bridge structure of graphene by etching the underlying h-BN. The selective etching at higher pressures demonstrates the potential of SF_6 for fabricating graphene based superconducting devices stacks which can be used to create highly sensitive bolometric device. These findings can contribute towards fabrication of electronic and optoelectronic devices from other 2D materials.

Acknowledgement : *This work was supported by U. S. Army OSD Phase II STTR contract W911NF23C0027 and bymatching funds from the Florida High Technology Corridor (I-4) Program.*

3:15pm **2D-WeA-5 Printed Contacts to Layered Materials**, ***Sharadh Jois***, *E. Lee, J. Fleischer, P. Li, T. Esatu, E. Quinn, A. Hanbicki, A. Friedman,* Laboratory for Physical Sciences

Over the last decade, there has been an outburst in novel layered materials and devices for advanced computing. The common techniques to create electrical contacts to layered materials rely on electron-beam lithography and photolithography that require polymeric resists that leave behind residues that can be impossible to clean. Several advances in lithography-based contact engineering to improve the quality of electrical contacts to layered materials have been pivotal in enabling basic research. The primary approach taken in these methods was to eliminate polymers from coming in direct contact with the active channel material and reduce defects induced by the deposition of metal films. The encapsulation of the active material with hexagonal boron nitride (h-BN) and creating edge contacts, nano-via contacts, or van der Waals contacts, have given the desirable two-fold benefit. However, these methods require many additional steps that consume several days of fabrication involving dry stamping to make the stack and several steps of lithography to etch undesired areas, deposit metal contacts, and lift-off. Each additional step adds failure modes and reduces device yield, thwarting the rapid prototyping of new devices with layered materials. Direct-write printing is capable of creating microscale metallic contacts in a single step. We demonstrate that printed contacts are an alternate method to achieve high-quality electrical contacts to different layered materials while evading the problems with lithography. We benchmark the printed devices using appropriate measurements, such as gating, resistance vs. temperature, or Hall. Our results show that direct-write printing can be used as an alternative to lithography to fabricate devices of layered materials for rapid testing. Furthermore, our work paves the way for creating printed circuits of layered materials for new applications.

3:30pm **2D-WeA-6 Electrical Transport of High-Quality CVD-Grown $MoSe_2$ Nanoribbons**, ***Y.-J. Leo Sun***, University of Maryland, College Park*; O. Ambrozaite, T. Kempa,* Johns Hopkins University*; T. Murphy,* University of Maryland, College Park*; A. Friedman, A. Hanbicki,* Laboratory for Physical Sciences

Two-dimensional (2D) materials such as transition metal dichalcogenides are excellent candidates for creating novel nano-electronic and photonic devices. Previous research indicates that the edge states of MoS_2 could strongly influence its conductivity, and the 2D honeycomb structure enables different electronic performance along the zigzag and armchair edges. Understanding and controlling the conductivity is essential in devices like field effect transistors that use MoS_2 as the channel. To date, transport along edge states of $MoSe_2$ nanoribbons, which have substantially reduced dimensionality relative to 2D crystals, has not been explored. In this project, we used chemical vapor deposition (CVD) to synthesize $MoSe_2$ nanoribbons through directed growth on phosphine (PH_3)-treated Si substrates. This approach yields directed growth of monolayer $MoSe_2$ to form narrow (< 1μm) nanoribbons. Tip-enhanced photoluminescence (TEPL) maps reveal a significant difference between the emission intensity at the edges and center of the nanoribbon. To perform electronic transport measurements, we used e-beam lithography to pattern contacts on the nanoribbons in a Hall bar configuration with the side contacts at the edges and tips of the nanoribbons. The nanoribbon was encapsulated by hBN flakes, and select regions were etched to facilitate the fabrication of edge contacts to reduce contact resistance. The influence of edge states on the electrical performance of $MoSe_2$ nanoribbons was investigated by conductivity and Hall transport measurements. Current flow in the transverse and longitudinal directions of the nanoribbon was compared to analyze the importance of edge states on $MoSe_2$ nanoribbon conductivity.

4:15pm **2D-WeA-9 Ultra-Low Energy Consumption Memory Study Using 2D Materials Heterostructures**, ***Young-Jun Yu***, Chungnam National University, Republic of Korea **INVITED**

Van der Waals (vdW) heterostructures using two dimensional (2D) atomic crystals have been attracted intensely for high performance as well as low-power memory applications. Furthermore, floating-gate (FG) memory devices based on 2D heterostructures exhibit stability with dielectric barriers such as hexagonal boron nitride (hBN) between semiconductors

and various charge storage layers. However, the reported operation voltage and energy consumption for hBN barriers cannot be reduced below several tens of volts. In this presentation, I will introduce ultrahigh energy efficiency of 2D material heterostructure-based memory devices for approaching to the biological synaptic energy level with employing ultrathin charge-trap layer underneath 2D semiconductor channel.

4:45pm **2D-WeA-11 2D Metal-Dielectric Hybrid Nanostructures via Electrochemical Deposition**, ***Chao Dun Tan***, *M. Buck,* University of St Andrews, UK

Often described as “surfaces without bulk”, carbon nanomembranes (CNMs) are an emerging class of dielectric 2D materials 1-2 nanometers thick. These membranes are derived from aromatic self-assembled monolayers (SAMs) which consist of highly ordered, upright-standing molecules that are formed by spontaneous adsorption at the substrate-liquid interface. By exposing these aromatic SAMs to low energy-electron irradiation, intramolecular bonds are cleaved, resulting in a two-dimensional network by crosslinking of the aromatic molecules. These nanomembranes are sufficiently robust to allow release from the substrate, transfer to other supports, and stacking to multiple layers, thus allowing the tuning from electron tunneling through single CNMs to insulating multilayers. Furthermore, their amorphous structure does not impose limitations with regard to scaling.

It is the electron transfer across monolayers that makes CNMs also an attractive platform for electrodeposition and the design of hybrid structures. The approach taken here contrasts established electrochemical applications of CNMs where they have been employed in area-selective electrodeposition to define passivating regions by exploiting the difference in charge transfer across CNMs and native SAMs. Investigating metal electrodeposition onto CNMs, deposition parameters (e.g. potential and time) allow control of nucleation and growth, thus enabling the morphologies of the deposits to range from individual metal nanoparticles to continuous layers. Moreover, exploiting the transferability of CNMs, the scheme offers the prospect to produce hybrid nanostructures defined by electrode structures which serve as reusable master patterns. Since CNMs are chemically inert, they have a large potential window and, thus, provide flexibility as regards electrolytes used and materials deposited. The possibility of generating templated metal/dielectric nanostructures may open pathways for the implementation of CNMs as nanocircuit boards in combination with other 2D materials, metamaterials, or nano-electromechanical systems (NEMS).

5:00pm **2D-WeA-12 Disentangling Anisotropic Resistivities of the Topological Insulator Bi_4Br_4**, ***Bert Voigtländer***, *J. Hofmann, S. Kovalchuk, V. Cherepanov, T. Balashov, F. Lüpke,* Forschungszentrum Juelich GmbH, Germany*; Z. Wang, Y. Yao,* Beijing Institute of Technology, China*; S. Tautz,* Forschungszentrum Juelich GmbH, Germany

Bi_4Br_4 is a promising higher-order topological insulator with a highly anisotropic crystal structure. In this material, topological edge states have been observed at room temperature. As a step towards nanoscale electric transport measurements through possible ballistic edge channels at step edges, we disentangle the resistivities of this material in all directions. We combine four-point resistance measurements in the square geometry on a bulk sample of Bi_4Br_4 with four-point resistance measurements on thin 2D flakes of this material in the linear configuration. These measurements give sufficient information to disentangle the two lateral resistivities along and perpendicular to the quasi-one-dimensional crystal structure, the latter being seven times lower than the conductivity along the atomic rows. Moreover, we can as well disentangle the vertical resistivity, which is much larger (~ 500 times) than the in-plane components. Due to degradation of this material under ambient conditions, we performed the electrical measurements under UHV conditions. Further, due to the micrometer sizes of the thin flakes of this material, a multi-tip scanning tunneling microscope was used to perform the four-point measurements on the micrometer scale.

5:15pm **2D-WeA-13 Electrical Breakdown of 2D Ruddlesden-Popper Metal Halide Perovskites**, ***Mengru Jin***, Texas A&M University*; E. Vasileiadou,* Northwestern University*; I. Spanopoulos,* University of South Florida*; K. Lee,* Texas A&M University*; M. Kanatzidis,* Northwestern University*; Q. Tu,* Texas A&M University

Abstract

2D Ruddlesden-Popper (RP) metal halide perovskites (MHPs) have emerged as promising low-cost, high-performance direct bandgap semiconductor materials in a plethora of energy and electronic applications, offering enhanced environmental stability compared to their conventional 3D analogues. Electrical breakdown (BD) in such devices signifies the cumulative degradation of the internal structure of the 2D MHPs, leading to loss of device functionality. Understanding the BD process, its mechanisms and inducements are critical for the commercialization of the semiconductor devices based on 2D MHPs. Here, we investigate the electrical BD behavior of a prototypical family of 2D RP MHPs, $(BA)_2MA_{n-1}Pbn I_{3n+1}$ (BA = butylammonium, MA = methylammonium cation, and n indicates the number of PbI_6^{4-} octahedra in one repeating unit), using conductive atomic force microscopy (C-AFM).Thin 2D MHP flakes were mechanically exfoliated onto conductive substrate directly from solution-grown single crystals using the scotch-tape method. I-V curves were obtained from flakes to quantify the breakdown strengths as a function of n, thickness and the ramping rate in a dry environment. When the applied bias surpasses a threshold voltage (defined as V_{BD}), the current will increase rapidly, which indicates the electrical BD and a hole will be burnt into the flake. Analysis of the hole depth revealed a layer-by-layer breakdown process very similar to that found in boron nitride (BN). The V_{BD} decreases with reductions in either the thickness or the sweep rate. Conversely, the BD strength exhibits an opposing trend, escalating as the thickness decreases. Furthermore, the BD strength increases with n, which reaches ~ 5.45×10^8 V/m for a monolayer 2D MHP with n = 5 at a ramping rate of 1 V/s. The BD strength is comparable to those of BN and self-assembled monolayer, implying good intrinsic reliability of 2D MHPs under electrical field. Our work provides the first systematic investigation of the electrical BD of 2D MHPs, which generates indispensable insights into guiding the 2D MHP materials and device design toward long-term durable applications.

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