2D Materials Focus Topic
Room: 310 - Session 2D+EM+MS+NS-FrM

2D Materials: Device Physics and Applications

Moderator: Daniel Gunlycke, Naval Research Laboratory

8:20am **2D+EM+MS+NS-FrM1 1, 2, 3... Ripples, Gaps and Transport in Few-layer Graphene Membranes**, ***ChunNing(Jeanie) Lau***, University of California, Riverside **INVITED**

Graphene, a two - dimensional single atomic layer of carbon, has recently emerged as a new model system for condensed matter physics, as well as a promising candidate for electronic materials. Though single layer graphene is gapless, bilayer and trilayer graphene have tunable band gaps that may be induced by out-of-plane electric fields or arise from collective excitation of electrons. Here I will present our results on mechanical manipulation and transport measurements in bilayer and trilayer graphene devices with mobility as high as 400,000 cm^2/Vs. We demonstrate ripple formation due to thermally or mechanically induced strain, the presence of an intrinsic gapped state in bilayer and trilayer graphene at the charge neutrality point and evidence for quantum phase transiition. Our results underscore the fascinating physics in these 2D membranes, and have implications for band gap engineering for graphene electronics and optoelectronic applications.

9:00am **2D+EM+MS+NS-FrM3 Photoinduced Doping in Heterostructures of Graphene and Boron Nitride**, ***Jairo Velasco Jr.***, *L. Ju,* UC Berkeley, *E. Huang,* Stanford University, *S. Kahn, C. Nosiglia, H.-Z. Tsai,* UC Berkeley, *W. Yang,* Beijing National Laboratory for Condensed Matter Physics, Republic of China, *T. Taniguchi, K. Wantanabe,* National Institute for Materials Science (NIMS), Japan, *Y. Zhang,* Fudan University, Republic of China, *G. Zhang,* Beijing National Laboratory for Condensed Matter Physics, Republic of China, *M.F. Crommie, A. Zettl, F. Wang*, UC Berkeley

Van der Waals heterostructures (VDH) provide an exciting new platform for materials engineering, where a variety of layered materials with different electrical, optical and mechanical responses can be stacked together to enable new physics and novel functionalities. Here we report an emerging optoelectronic phenomenon (i.e. photo-induced modulation doping) in the graphene-boron nitride VDH (G/BN heterostructure). We find it enables flexible and repeatable writing and erasing of charge doping in graphene with visible light. We demonstrate that the photo-induced modulation doping maintains the remarkable carrier mobility of the G/BN heterostructure, and it can be used to generate spatially varying doping profiles like *pn* junctions. Our work contributes towards understanding light matter interactions in VDHs, and innovates a simple technique for creating inhomogeneous doping in high mobility graphene devices. This opens the door for new scientific studies and applications.

9:20am **2D+EM+MS+NS-FrM4 Two-dimensional Resistance Map of Graphene p-n Junction in the Quantum Hall Regime**, ***NikolaiN. Klimov,*** *S. Le, C.A. Richter,* National Institute of Standards and Technology (NIST), *J. Yan,* University of Massachusetts, Amherst, *E. Comfort, J.U. Lee,* SUNY-University of Albany, *D.B. Newell*, National Institute of Standards and Technology (NIST)

Graphene, a two dimensional (2D) electronic system with a unique band structure, is a promising material for future electronic devices, especially for electrical metrology [1]. Currently, devices based upon GaAs heterostructures 2D electron gases (GaAs-2DEG) are used to realize a single quantum resistance standard value of $(½)h/e^2$ = 12,906.4035 Ω with metrological accuracy. It is important to realize resistance values over a wider resistance scale to expand the technical relevance of quantum resistance standards.

In the past, attempts have been made by using parallel or series GaAs-2DEG Hall bars to achieve multiple or fractional resistance values of h/e^2. However, the difficulties of fabricating ideal contacts and metal interconnects between the Hall bars severely limit the yield of properly operating devices. Graphene, with its ability to create both electron and hole 2D gases on a single Hall bar device without metal interconnects, is an ideal platform to overcome this difficulty [2].

We have fabricated a graphene FET p-n junction device in a Hall bar geometry and experimentally characterized it at large magnetic fields to determine the range of quantized resistance values that can be obtained. The device features two doped polysilicon split gates that are buried in a SiO_2 substrate within 100 nm-150 nm from the surface of graphene. The fabrication process achieves an atomically smooth dielectric surface, which is needed to preserve the intrinsic band structure of graphene. Independent voltage control on these gates allows separate tuning of both type and concentration of charge carries in the two parts of graphene conducting channel. In addition, a very narrow 150 nm gap between split gates gives a very sharp junction. Measurement of the sample's resistance at different gate values and measurement configurations in the quantum Hall regime allows us to fully characterize the device and to obtain multiples or fractions of the resistance value h/e^2 . We will show that our experimental results can be explained by the Landauer-Büttiker edge-state transport model with the assumption of a partial mixing at the p-n interface. Potential application of graphene p-n junction devices for resistance standards with a wide range of resistance values other than $h/2e^2$ will be discussed.

References:

[1] A. Tzalenchuk, *et al.,* Nature Nanotech., 5, 186 (2010)

[2] M. Woszczyna, *et al.,* APL, 99, 022112 (2011)

9:40am **2D+EM+MS+NS-FrM5 Electrical Breakdown and Current Carrying Ability of Multilayer MoS_2 Transistors**, ***Philip Feng***, *R. Yang, Z. Wang*, Case Western Reserve University

We report the first study of electrical breakdown of multilayer molybdenum disulphide (MoS_2) transistors through precision electrical measurements and simulation that shows the effect of varying the device size and conductivities on the breakdown limit. We demonstrate that the multilayer devices have better current carrying capabilities compared to thin layer devices. We also study the effect of varying MoS_2 thickness upon electron mobility in the channel.

MoS_2 has recently emerged as a new two-dimensional (2D) semiconducting crystal with attractive properties, such as the absence of dangling bonds, high thermal stability, and having a thickness-dependent bandgap [#_edn1]. While prototype single- and few-layer MoS_2 FETs and circuits have been demonstrated, in practice multilayer (up to 10s of nanometers) devices may be more desirable for certain applications: they can have higher carrier mobility and density of states under the same dielectric environment, greater mechan ical strength, higher current limit and better manufacturability [#_edn2]' [#_edn3]. While the breakdown of single layer MoS_2 transistors has been demonstrated [#_edn4], breakdown of multilayer devices has not been studied.

In this work, we study the electrical breakdown of devices with different thicknesses through experimental demonstration and simulation with finite element method (FEM). We observe that the breakdown process happens gradually with multiple voltage sweeping cycles, and thicker devices generally show higher breakdown current, which is also demonstrated in the simulation. The highest breakdown current in the measurement is 1.2mA, which is one of the highest current reported results so far for MoS_2 transistors. Simulation also shows that with higher conductivity channel, the breakdown current and breakdown current density both increase. The high field transport characteristics of multilayer MoS_2 transistors demonstrate that the devices could drive high loads in circuits and could be used for circuits that require high power or current. The thickness dependence of mobility shows that the device performance can be further improved by carefully tuning the device parameters.

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[i] [#_ednref1] Q. H. Wang, *et al.*, *Nat. Nanotechnol.* **7**, 699 (2012).

[ii] [#_ednref2] D. Jariwala, *et al.*, *ACS Nano* **8**, 1102 (2014).

[iii] [#_ednref3] R. Ganatra, Q. Zhang, ACS Nano (2014), DOI: 10.1021/nn405938z.

[iv] [#_ednref4] D. Lembke, A. Kis, *ACS Nano* **6**, 10070 (2012).

10:00am **2D+EM+MS+NS-FrM6 Lithography-free Fabrication of Graphene Devices**, ***Nick Thissen,*** *R.H.J. Vervuurt,* Eindhoven University of Technology, Netherlands, *J.J.L. Mulders,* FEI Electron Optics, Netherlands, *J.W. Weber, A.J.M. Mackus, W.M.M. Kessels, A.A. Bol*, Eindhoven University of Technology, Netherlands

Graphene device fabrication on large-area graphene typically involves several patterning steps using electron beam or optical lithography, followed by graphene etching and metallization for application of metallic contacts. However, the resist films and lift-off chemicals used in lithography introduce compatibility issues, such as the difficulty of removing the resist from the graphene. This resist residue has a negative influence on the thermal and electrical properties of the graphene and interferes with functionalization of the graphene. This motivates the development of a 'bottom-up', direct-write, lithography-free fabrication method.

In this work, a lithography-free fabrication method for graphene-based devices was developed. As a first step, the method involves direct

patterning of large-area graphene by focused ion beam (FIB) in order to isolate graphene from the bulk. The patterning of the graphene is performed in a DualBeam (SEM / FIB) system, in which a 30 kV FIB is used to locally remove graphene from the substrate. An *in situ* Raman microscope allows for direct observation of the graphene quality before and after FIB processing, from which it was determined that a low Ga-ion dose of 10 C/m^2 is sufficient for complete graphene removal. By optimizing the pattern design, the ion beam current and the background pressure in the DualBeam system, unintentional damage of the graphene by scattered ions is almost completely prevented.

After FIB patterning, as a second step a direct-write atomic layer deposition (ALD) technique is applied in the same system to locally deposit contacts to the isolated graphene. In the direct-write ALD technique, the patterning capability of electron beam induced deposition (EBID) is combined with the material quality of ALD. A thin seed layer consisting of small Pt grains in amorphous carbon is deposited on the graphene by EBID in the desired contact pattern. Subsequently, a selective ALD process purifies the seed layers and builds them into high-quality Pt contacts. This combined approach yields virtually 100% pure Pt (resistivity of 12 μΩcm) with a lateral resolution of 10 nm[1]. This chemical approach to contact deposition is expected to yield lower contact resistances compared to conventional physical deposition techniques.

By combining patterning and direct contact deposition in the same system, graphene devices were fabricated from large-area graphene without the use of lithography. First results from sub-optimal devices demonstrate field-effect mobilities approaching 500 cm^2/Vs and contact resistances as low as (40 ± 30) Ω.

[1] A.J.M. Mackus et al., *Nanoscale* **4**, 4477 (2012)

10:40am **2D+EM+MS+NS-FrM8 Electronic Transport in Transition Metal Dichalcogenides**, ***Joerg Appenzeller***, Purdue University **INVITED**

Since the discovery of graphene for electronic applications, there has been a substantial worldwide effort to explore other layered materials. Transition metal dichalcogenides (TMDs) like MoS_2, $MoSe_2$, or WSe_2, to just name a few, not only offer the desired ultra-thin body structure that translates into superior electrostatics as desirable for nanoelectronics applications, but also exhibit a sizable band gap. While to date the ideal application space for these materials has not been identified, it is obvious that only through a detailed understanding of the underlying transport in these layered materials intrinsic properties that lend themselves to particular applications can be uncovered.

In my presentation I will first discuss the benefits of an ultra-thin body structure for scaled tunneling FET applications including tunneling devices. Contacts play a particularly crucial role in this context and can easily mask the intrinsic performance of TMDs as will be discussed based on experimental Schottky barrier tunneling data obtained from MoS_2, $MoSe_2$ and WSe_2 field-effect transistors. A careful analysis of all these material systems reveals details about Schottky barrier heights for electron and hole injection as well as the band gap. These findings are then put into the context of channel length scaling and layer thickness dependence of three-terminal TMD devices based on MoS_2 transistors. Last, experimental data on the band-to-band tunneling in partially gated WSe_2 device structures will be discussed and projections about the potential usefulness of TMDs for tunneling device applications will be made.

11:20am **2D+EM+MS+NS-FrM10 Controlled Synthesis and Fuel Cell Application of Carbon Nanowalls**, ***Hiroki Kondo***, *S. Imai, K. Ishikawa, M. Sekine, M. Hori,* Nagoya University, Japan, *M. Hiramatsu*, Meijo University, Japan

Carbon nanowalls (CNWs) are one of carbon nanomaterials and contain stacks of graphene sheets vertically standing on a substrate. Each wall with the top edge is continuous crystallographically through bending or branching and composed of nanographite domains. Recently, we have developed the formation method of the ultra-high-density over 10^{13} cm^{-2} Pt nanoparticles on the whole surface area of the CNWs with a diameter of 2-3 nm employing metal-organic chemical fluid deposition (MOCFD) method in supercritical fluid (SCF). They are promising as a catalytic electrodes for a polymer electrolyte fuel cell because of its high-specific-surface-area and high aspect ratio. On the other hand, while it is known that Pt nanoparticles are poisoned by CO below 100°C, it is reported that Pt-Au nanoparticles are excellent candidate for a low-temperature anode electrocatalyst. In this study, supporting processes of Pt-Au nanoparticles on the CNWs using the SCF-MOCFD method and their catalytic properties were investigated.

We used the SCF-MOCFD system to support Pt and Au nanoparticles on the CNWs. Firstly, Pt nanoparticles were supported using 1wt% $(CH_3C_5H_4)(CH_3)_3Pt$ solution (2 ml). Then, Au nanoparticles were subsequently supported using $(CH_3)_2Au(CH_3COCHCOCH_3)$ solution (1 ml). Both precursors were diluted by n-hexane $[CH_3(CH_2)_4CH_3]$.

According to the SEM images of the CNWs after the supporting processes of only Pt nanoparticles and, both Pt and Au ones, the nanoparticles are supported on the entire surface area of each CNWs in the both cases. It is also found that the diameter and its distribution of the nanoparticles decrease after the second Au supporting process, while its density increases. This means that the relatively large Pt nanoparticles are effectively removed and small Au nanoparticles are simultaneously supported at the second supporting process. On the other hand, we evaluated cyclic voltammetry (CV) characteristics using CNWs with different-density Pt nanoparticles, in which density of $3.0x10^{12}$ $cm^{-2}$and diameter of 1.1 nm obtained for 10 min supporting and, density of $8.3x10^{12}$ and diameter of 1.5 nm obtained for 30 min supporting. Peaks related to adsorption and desorption of hydrogen were found in both cases. With increasing the supporting time, the specific surface area of Pt evaluated from the CV about twofold increased. However, according to the the TEM images, the ratio of surface area of Pt nanoparticles are about fivefold. It is deduced that some parts of Pt nanoparticles are inactive. Therefore, there results indicate that not the crystallinity control of CNWs are essential to improve the catalytic performance.

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