INVITED TALKS - ABSTRACTS

“Buckled Atomic Sheets: The Intriguingly Complex Case of Phosphorene and Silicene”

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Buckled atomic sheets such as phosphorene and silicene promise interesting anisotropic phenomena and strongly coupled multi-physics. Experimental properties and ageing effect are among the biggest topics. Here, we report key results of critical importance for device studies and understanding including phosphorene devices featuring: i) record mobility ($\mu$) $\sim$1560 cm$^2$/V.s about an order of magnitude higher than other 2D semiconductors, ii) ambipolar current saturation that is more desirable for optoelectronics than graphene because of its sizeable direct bandgap, and iii) the first demonstration of flexible devices and circuits. Experimental results on silicene represents the first device investigation that is enabled by advanced materials growth and a unique sandwich transfer process, and confirm the graphene-like Dirac transport. In addition, the common air-stability issue of great concern is investigated with microwave impedance microscopy (MIM) revealing that ordinary methods such as Optical and AFM are generally blind as an evaluation technique. Silicene and phosphorene materials show long-term air-stability with engineered protection. Collectively, the record mobility of phosphorene makes it the most compelling 2D semiconductor, while silicene’s allotropic affinity with bulk Si and its low-T growth suggests a more direct path for semiconductor technology integration.

“MoS2 and Dichalcogenide-Based Devices and Hybrid Heterostructures”

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MoS2 and transition metal dichalcogenides have opened numerous research directions and potential applications for this diverse family of nanomaterials. The combination of these 2D materials in heterostructures can result in a huge number of potentially interesting new materials. Most of the attention in this field is focused on heterostructures composed of different 2D materials. In my talk, I will present some of our recent efforts in this direction, oriented towards realizing combinations of 2D and 3D materials into van der Waals heterostructures. I will report on high-performance photodetectors based on 2D/3D heterostructures that can operate with internal gain and high sensitivity. Our devices also show very low noise, due to the unique architecture of the 2D/3D heterojunction. Next, I will give an update on our efforts to realize high-performance electrical circuits based on TMD materials.

“2D Crystals for Nanoelectronics and Beyond”
The experimental demonstration of graphene in 2004, a truly one-atom thick layer of carbon atoms, has opened up a window to the two-dimensional (2D) world of materials. This has subsequently triggered a surge of research activities on various 2D crystals including single layers of hexagonal-boron nitride (h-BN), several dichalcogenides (such as MoS$_2$ and WSe$_2$), and complex oxides, which have been successively prepared using the micromechanical exfoliation technique employed for graphene. The ease of preparing these 2D crystals for demonstrating various prototype applications relies on the layered structures of their 3D bulk materials, where adjacent layers are held together by the relatively weak van der Waals bonds, while strong valence bonds firmly pack the in-plane atoms together. Two common features shared by all 2D crystals are the atomic scale thickness, which leads to novel physics and interesting applications, and the pristine interfaces that potentially promise stable chemical, electrical, and thermal characteristics. Atomic scale thicknesses (few Å/layer) of 2D semiconducting crystals and their controllable precise band gaps as a function of number of layers also enable the scaling of electronic devices without inducing performance variations. Moreover, seamless planar synthesis and stacking of various 2D crystals can be exploited to build novel lateral and vertical heterostructures, respectively. This talk will highlight and discuss the prospects of such 2D crystals for designing low-power, low-loss and ultra energy-efficient active and passive devices targeted for designing next-generation green electronics. It will also bring forward some applications uniquely enabled by 2D crystals, including sensors and high-frequency devices and circuits for improving quality of life, and discuss related challenges and opportunities.

“From Band Structures to Devices in 2D Dichalcogenides”

Guido Burkard
University of Konstanz, Germany

The monolayer transition-metal dichalcogenides (ML-TMDCs) are truly two-dimensional (2D) semiconductors, which hold great appeal for electronics, opto-electronics, and spintronics and have been demonstrated in FETs, logical devices, and optoelectronic structures (for a review, see e.g. [1]). We have investigated ML-TMDCs using the k.p approach aided by density functional theory (DFT), finding trigonal warping and electron-hole asymmetries [2]. Unlike graphene, the ML-TMDCs lack inversion symmetry leading to interesting spin-orbit effects, both in the valence and conduction bands [3]. The resulting effective band Hamiltonians can be used to describe electronic properties in nanostructures and devices [3].


“2D TMDC Materials: Engineering Light-Matter Interactions at the Atomic-Scale”
Two-dimensional (2D) transition metal dichalcogenide (TMDC) materials such as MoS$_2$, MoSe$_2$, WS$_2$, and WSe$_2$ present an attractive platform that may enable the development of atomic-scale photonics devices with exotic functionalities. However, much fundamentals of the light-matter interaction at 2D TMDC materials has remained elusive. In this talk, I will first report our studies on the dielectric function of atomically thin MoS$_2$ films with a layer number ranging from one to ten. The dielectric function, which dictates the nature of light-matter interaction, shows an anomalous dependence on the layer number of the film, decreasing and then increasing with a continuous increase of the layer number. We demonstrate that this is because the contribution of excitons to the dielectric function dominates over the contribution of band structures for the MoS$_2$ films less than 5 layers thick. This is in stark contrast with conventional materials, whose dielectric function is usually dominated by the effect of band structures. By leveraging on the knowledge of the dielectric function, we have theoretically and experimentally designed to enable perfect absorption in atomically thin MoS$_2$ films for a narrow band incidence (~ 20 nm). We have also successfully enabled strong absorption in atomically thin MoS$_2$ films for solar radiation (> 85%).
"Light-Matter Interaction in Superlattices and Heterostructures Made of 2D Crystals"

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The isolation of various two-dimensional (2D) materials allows for the possibility to combine them into heterostructures. Such a concept can be used to study particular phenomena such as the metal-insulator transition [1], Coulomb drag [2], Hofstadter’s butterfly [3], or to make functional devices such as tunnel diodes [4], tunnelling transistors [5, 6], photodetectors [7] and light emitters [8]. The range of functionalities and performance are likely to be further improved by increasing the number of components in the heterostructure and by improving their electronic quality. Such complex heterostructures are currently fabricated by using mechanically exfoliated 2D crystals. Therefore, alternative low cost and mass-scalable methods should be utilized to bring the attractive qualities of 2D crystal based heterostructures into real-life applications.

I will show that the ink-based technology is suitable for fabrication of low cost and flexible devices based on heterostructures of arbitrary complexity [9]. The success of this technology does not only depend on the performance of the devices, but also on the nature of the ink. Currently, 2D crystal inks are mostly based on organic solvents [10], which are toxic, expensive and have high boiling point, which affects post-processing. Water is very attractive as solvent, but it is not able to exfoliate graphite and it is also not suitable for inkjet printing, which is a very attractive technique for flexible electronics. We recently developed a method to produce highly concentrated and oxygen-free graphene dispersions in water [11]. The graphene coatings produced with those inks also show high thermal conductivity, compared to Diamond-like carbon films of similar density [12]. Furthermore, by modifying the exfoliation process, we have been able to produce water-based inks compatible with inkjet printing technology. The method can be extended to make 2D crystal inks of any layered material (hBN, MoS2, WS2, etc [13]), making possible to build a whole heterostructure by inkjet printing different water-based inks [14].

11. H. Yang et al, Carbon, DOI: 10.1016/j.carbon.2012.11.022
14. Filed patent
Two-dimensional transition metal dichalcogenides (2D TMDs) — whose generalized formula is MX$_2$, where M is a transition metal of groups 4–7 and X is a chalcogen — consist of over 40 compounds. Complex metal TMDs assume the 1T phase where the transition metal atom coordination is octahedral. The 2H phase is stable in semiconducting TMDs where the coordination of metal atoms is trigonal prismatic. High performance of electronic and opto-electronic devices have been demonstrated with semiconducting TMDs while interesting condensed matter effects such as charge density waves and superconductivity have been observed in bulk metallic 1T phase TMDs. However, stability issues have hampered the study of interesting phenomena in two-dimensional 1T phase TMDs. Recently there has been a surge of activity in developing methodology to reversibly convert 2D 2H phase TMDs to 1T phase. In contrast with typical phase transformation conditions involving pressure and temperature, phase conversion in TMDs involves transformation by chemistry at room temperature and pressure. Using this method, we are able to convert 2H phase 2D TMDs to the 1T phase or locally pattern the 1T phase on 2H phase 2D TMDs. The chemically converted 1T phase 2D TMDs exhibit interesting properties that are being exploited for catalysis for hydrogen evolution reaction, source and drain electrodes in high performance field effect transistors, and as electrodes for energy storage. In this contribution, I will summarize the key properties of 2D 1T phase TMDs and their applications as electrodes for energy and electronics.

Photocurrent microscopy involves measuring the short-circuit current generated by a sample when a laser is focused at a point or scanned over it. Photocurrent in 2D devices at zero magnetic field is generated only near contacts, junctions and inhomogeneities. We find that in an applied perpendicular magnetic field additional photocurrent is generated near the sample edges. It can be understood as resulting from the photo-Nernst effect, where a current density is induced perpendicular to the laser-induced temperature gradient. It thereby gives a means of measuring the Nernst coefficient in two-terminal devices. The local excitation gives rise to a photocurrent in distant contacts owing to charge continuity, and the results are captured well by formula recently derived by Levitov and Song. At high magnetic fields the photocurrent shows strong quantum oscillations, which can be understood using a combination of a generalized Mott formula and edge-state effects to yield information about Fermi surfaces and quantum Hall states.
Over the last few years, liquid phase exfoliation (LPE) has become an increasingly important technique for the production of two-dimensional nanomaterials. This method involves the exfoliation of layered crystals, usually by exposure to ultra sonication or high shear rates, to form large quantities of two-dimensional nanosheets stabilized in liquids. This greatly facilitates further processing such as size-selection, formation of thin films or composites. Importantly, LPE has been further developed and scaled-up since the first reports on graphene production in 2008. This has led to the commercialization of this method as a graphene production technique. Possibly, the greatest strength of LPE is its versatility as it can be applied to a broad range of layered materials beyond graphene such as BN, transition metal dichalcogenides (MoS$_2$, WS$_2$, MoSe$_2$, etc), layered oxides (MoO$_3$), III-VI semiconductors (GaS) or black phosphorus.

The ability to produce this variety of exfoliated new materials and to control size and thickness by further liquid processing is of interest for both basic studies and applications. For example, edge and confinement effects change the optical properties of the materials. We were able to use this to quantitatively relate spectral changes of the extinction and absorbance spectra to the lateral size and/or thickness for a number LPE nanosheets (graphene, MoS$_2$, WS$_2$, GaS). This offers a very powerful, high-throughput characterization that can be used to produce samples of controlled size and thickness very easily. We also show that size-control in turn is important to explore the applications’ potential of these materials in areas as diverse as electrocatalysis, composite reinforcement or inkjet-printed devices. For example, polymer reinforcement requires large nanosheets, while catalytic sites are located at edges making small nanosheets beneficial.
“2D Materials: Prospects for Electronics”

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The isolation of graphene now almost a decade ago has given rise to the revitalization of two-dimensional materials (2DM). The 2DM materials under investigation, in addition to graphene, include hexagonal boron nitride (h-BN), semiconducting, metallic, and superconducting, transition metal dichalcogenides (TMD). While h-BN is an excellent 2D insulator, TMD materials provide what neither graphene nor h-BN can, bandgap engineering that, in principle, can be used to create devices that cannot be fabricated with h-BN and graphene. Therefore, there is hope to integrate these materials for selected device types for many applications ranging from inkjet printing, photonic applications, flexible electronics, and high performance electronics. In addition, before the engineering community can develop these products that use 2DM, basic material properties for each application needs full definition so as to select the most appropriate techniques for material preparation and growth. A number of deposition techniques have been used to prepare large area graphene, growth on SiC, precipitation of carbon from metals, and chemical vapor deposition (CVD) on Cu and Ge. TMDs present different opportunities and difficulties in the preparation of low defect density large area single crystals. Vapor transport, CVD, and molecular beam epitaxy are being used to produce these materials for initial studies of materials physics device fabrication. A number of devices structures are currently under evaluation to take advantage of the basic properties of graphene, bi-layer graphene, h-BN and TMDs. Some of the devices are based on tunneling which can be used to lower the voltage and power dissipation of a logic gate. The tunnel field-effect transistor (TFET) is one example where the shape of the tunnel barrier is modulated with a gate bias to beat the 60 mV/decade subthreshold swing limit in transistors. Extraordinary current-voltage characteristics are also achieved in 2D-to-2D heterostructure stacks consisting of a low bandgap TMD or graphene, a higher bandgap TMD or hBN, and a low bandgap 2DM. Using top and bottom gates, one achieves high tunneling currents only when one satisfies energy and momentum conservation in the tunneling process, leading to negative differential resistance, and new opportunities for circuits. In this presentation we will review the state of the art in devices in graphene, h-BN, and a few TMD materials and their prospects for future electronic device applications.

“Bandstructure Engineering in Bilayer Graphene with Large Displacement Fields”

Klaus Ensslin
ETH Zurich, Switzerland

Bilayer graphene is a unique system where both the Fermi energy and the low-energy electron dispersion can be tuned. This is brought about by an interplay between trigonal warping and the band gap opened by a transverse electric field. In particular one can observe a transition in Fermi line topology as a function of carrier density and vertical electric field. Large vertical electric fields in bilayer graphene allow to open a band gap whose magnitude as determined from temperature-dependent transport experiments is typically much smaller than theoretically predicted. Such a local band gap control is envisioned as a way to realize electrostatically defined graphene nanostructures. We discuss the prospects of such an approach both in terms of sample technology (dry pick up of van der Waals heterostructures) and experimental opportunities.
“Three-Particle Charged Complexes in TMDC Optics”

Vladimir Falko
Lancaster University

We have compared binding energies of trions $X^\pm$, with binding energies of localised charged complexes [Phys. Rev. Lett. 114, 107401 (2015)]: excitons bound by a donor/acceptor charge $X^{D/A}$, and overcharged acceptors/donors in two-dimensional atomic crystals of transition metal dichalcogenides. The problem was solved both by mapping the three-body problem in two dimensions onto one particle in a three dimensional potential treatable by a purposely-developed boundary-matching-matrix method and using diffusion quantum Monte Carlo approach. They have found that in monolayers of transition metal dichalcogenides the dissociation energy of $X^\pm$ is typically much larger than that of localised exciton complexes, so that trions are more resilient to heating as compared to defect-localised excitons, despite the fact that their recombination line in optics is less red-shifted from the exciton line than the line of $X^{D/A}$.

“Challenges and Opportunities of 2D Materials for Electronic Applications”

G. Fiori, G. Iannaccone
University of Pisa, Italy

In this talk, we will focus on the perspectives and challenges of 2D materials for electronic applications. In particular, we will provide insight on the physical mechanisms playing at the nanoscale through numerical simulations, while assessing the performance against Industry requirements for next technological nodes. To this purpose, we will discuss the 2D materials, which offer the best opportunities to be exploited as channel materials in devices meant for digital applications (both High performance and Low-power), as well as for Analog Applications (e.g. Radio Frequency). We will also spend part of the presentation talking on applications rather than electronics, and in particular on solar cells, where we believe graphene can make the difference in the short-midterm.

“Engineering Electron and Hole Wires in 2D Materials through Polar Discontinuities”

Marco Gibertini
EPFL, Lausanne, Switzerland

First-principles quantum-mechanical simulations are heralding a revolution in our capabilities to understand, predict, and design novel materials for optimal properties and performance. In this talk I will offer some examples of this paradigm in the prediction of the electronic and thermal properties of two-dimensional materials. Particular emphasis will be given to the suggestion of engineering polar discontinuities in honeycomb lattices, driving the emergence of one-dimensional electron or hole wires. Several realistic approaches are discussed, based on 1) nanoribbons, where a polar discontinuity against the vacuum emerges; 2) functionalizations, where covalent ligands are used to introduce polar discontinuities by selective or total functionalization of the parent systems; and 3) on phase engineered interfaces. All the cases considered have the potential to deliver innovative applications in ultra-thin and flexible solar-energy devices and in micro- and nano-electronics.
Two-dimensional (2D) solids – the thinnest materials available to us – offer unique properties and a potential path to device miniaturization. The most famous example is graphene, which is an atomically thin layer of carbon atoms bonded together in-plane with sp² bonds. Recently, an entirely new family of 2D solids – transition metal carbides (Ti₂C, Ti₃C₂, Nb₄C₃, etc.) and carbonitrides – was discovered by Drexel University scientists [1,2]. Selective etching of the A-group element from a MAX phase results in formation of 2D Mₙ₊₁Xₙ solids, labeled “MXene”. Eleven different carbides and carbonitrides have been reported to date [2-5]. Structure and properties of numerous MXenes have been predicted by the density functional theory, showing that MXenes can be metallic or semiconducting (up to 2 eV band gap), depending on their surface termination. Their elastic constants along the basal plane are expected to be higher than that of the binary carbides. Oxygen or OH terminated MXenes, are hydrophilic, but electrically conductive. Hydrazine, urea and other polar organic molecules can intercalate MXenes leading to an increase of the c lattice parameter of MXenes [3]. When dimethyl sulfoxide was intercalated into Ti₃C₂, followed by sonication in water, a stable colloidal solution of single- and few-layer flakes was produced. One of the many potential applications for 2D Ti₃C₂ is in electrical energy storage devices, such as batteries, Li-ion capacitors and supercapacitors [4,6]. Cations ranging from Na⁺ to Mg²⁺ and Al³⁺ intercalate MXenes. Ti₃C₂ paper electrodes, produced by vacuum assisted filtration of an aqueous dispersion of delaminated Ti₃C₂, show a higher capacity than graphite anodes and also can be charged/discharged at significantly higher rates. They also demonstrate very high intercalation capacitance (up to 900 F/cm³) in aqueous electrolytes.


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“Group IV Graphane Analogues”

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Similar to how carbon networks can be sculpted into low-dimensional allotropes such as fullerenes, nanotubes, and graphene with fundamentally different properties, it is possible to create similar “allotropes” of Ge or Sn with unique optoelectronic properties as well. Here, we will describe our recent success in the creation of hydrogen and organic-terminated group IV graphane analogues, from the topochemical deintercalation of precursor Zintl phases, such as CaGe₂. We will discuss how the optical, electronic, and thermal properties of these materials can be systematically controlled by substituting either the surface ligand or via alloying with other Group IV elements. Additionally, we have also developed an epitopotaxial approach for integrating precise thicknesses of Germanane layers onto Ge wafers that combines the epitaxial deposition of CaGe₂ precursor phases with the topotactic interconversion into the 2D material. Finally, we will describe our recent efforts on the preparation of Sn-containing graphane alloys in order to access novel topological phenomena predicted to occur in these graphanes.
Graphene material exhibits a number of outstanding electronic and mechanical properties that make it very attractive for micro and nanoelectronics applications. Considering graphene field effect transistors (GFETs), considerable efforts have been made during the recent years to reach impressive current gain cut-off frequency ($f_t$) over 400 GHz. Unfortunately the maximum frequency of oscillation ($f_{max}$) of GFETs remains under 100GHz. This low ratio $f_{max}/f_t$ is a drawback for HF applications.

The most urgent issues to be addressed are the absence of current saturation, and the degradation of mobility due to the underlying substrate. In this presentation, based on the small signal equivalent circuit, we will focus on the methodologies to improve the high frequency performances of the GFETs. This can be obtained by (i) developing new process technology optimized for graphene electronics devices (ii) pairing graphene to new 2D material (such as h-BN) material, (iii) developing new device topologies such as back-gated devices offering high flexibility such as control of contact doping, channel, ....

The presentation will be illustrated with some of the results of the WP4 (HF electronics) of the Graphene Flagship project.

In this paper we discuss recent advances in our understanding of the optical properties of monolayers of the transition metal dichalcogenide (TMDC) materials, including MoS$_2$, MoSe$_2$, MoTe$_2$, WS$_2$, WSe$_2$. These materials share several unusual characteristics, including a transition from an indirect-gap material in the bulk to a direct-gap, emissive material at monolayer thickness. They also exhibit selectivity to excitation of the degenerate K or K’ valley under circularly polarized radiation.

In our discussion we will highlight progress in understanding two types of interactions in these materials: the many-body interactions between charge carriers in one layer and interactions between carriers that arise when two monolayer sheets of materials stacked on one another to form a bilayer.

The many-body electronic interactions in monolayer TMDC crystals play a central role in defining their optical properties. Here we will stress recent spectroscopic studies in which we have identified the progression of excited exciton states in precise absorption measurements. This study directly reveals exciton binding energies of several hundred meV. A strongly non-hydrogenic disposition of levels is also observed.

Another unusual type of interaction associated with these materials concerns the electronic states and transitions expected in stacks of TMDC monolayers. We will present results of studies of the optical response of stacks composed of two monolayers the same material (but with an adjustable twist angle) and bilayers of two different crystals.
Two-dimensional materials have emerged as promising candidates for next-generation electronic and optoelectronic applications. As is common for new materials, much of the early work has focused on measuring and optimizing intrinsic properties on small samples (e.g., micromechanically exfoliated flakes) under idealized conditions (e.g., vacuum and/or cryogenic temperature environments). However, real-world devices and systems inevitably require large-area samples that are integrated with dielectrics, contacts, and other semiconductors at standard temperature and pressure conditions. These requirements are particularly challenging to realize for two-dimensional materials since their properties are highly sensitive to surface chemistry, defects, and the surrounding environment. This talk will thus explore methods for improving the uniformity of solution-processed two-dimensional materials with an eye toward realizing scalable processing of large-area thin-films. For example, density gradient ultracentrifugation allows the solution-based isolation of transition metal dichalcogenides (e.g., MoS$_2$, WS$_2$, MoSe$_2$, and WSe$_2$) and boron nitride with homogeneous thickness down to the single-layer level. Similarly, two-dimensional black phosphorus is isolated in solution with the resulting flakes showing field-effect transistor mobilities and on/off ratios that are comparable to micromechanically exfoliated flakes. In addition to solution processing, this talk will also report on the integration of two-dimensional materials with dielectrics and other semiconductors. In particular, atomic layer deposition of dielectrics on two-dimensional black phosphorus suppresses ambient degradation, thereby preserving electronic properties in field-effect transistors at atmospheric pressure conditions. Finally, p-type semiconducting carbon nanotube thin films are combined with n-type single-layer MoS$_2$ to form p-n heterojunction diodes. The atomically thin nature of single-layer MoS$_2$ implies that an applied gate bias can electrostatically modulate the doping on both sides of the p-n heterojunction concurrently, thereby providing five orders of magnitude gate-tunability over the diode rectification ratio in addition to unprecedented anti-ambipolar behavior when operated as a three-terminal device.

Wide Hogenhout
EU Flagship Office

Flagship projects funded under the EU’s Research Framework programme are visionary, science-driven, large-scale research initiatives addressing grand Scientific and Technological challenges. They are long-term initiatives bringing together excellent research teams across various disciplines, sharing a unifying goal and an ambitious research roadmap on how to achieve it. In October 2013 the European Commission launched two such Flagship projects: Graphene and The Human Brain Project (HBP). Each will have a budget of around 1 billion Euros for 10 years, half of which is planned to come from the EU funds. The other half would come mainly from the EU Member States and possibly the private sector. With the Flagships, the Commission launched a new partnering model for long term cooperative research in Europe. The Graphene Flagship has 142 partners in 23 countries, of which almost one third are industrial.

Through this partnership, the aim is to develop material technologies for graphene and related materials, create new device concepts and component technologies and integrate these with existing technologies, in order to bring graphene to a variety of applications. This will contribute to the top priority of boosting economic growth, while contributing to sustainable development through energy efficient and environmentally friendly products. Wherever relevant, graphene will establish collaborations to benefit from all possible synergies and to fully play their role of globally leading research initiatives. Where there is strategic value and reciprocal benefits, the Commission promotes the establishment of international collaboration agreements, within a context of creating wider coalitions for addressing global scientific challenges.
For the integration of 2D materials into optoelectronic highspeed circuits, it is essential to understand the picosecond transport dynamics of photogenerated charge carriers during their optical lifetime in these materials. Conventional electronic measurements cannot resolve such ultrafast dynamics because available electronic equipment cannot produce trigger signals and detect transients faster than tens of picoseconds. Furthermore, devices based on 2D materials typically exhibit a high impedance of several kilo-ohms, and ultrafast charge-carrier dynamics are therefore obscured by the response time of the high-frequency circuits. We describe an experimental on-chip pump/probe scheme to measure the photocurrent dynamics of electrically contacted 2D materials with a picosecond time-resolution [1]. We particularly highlight the non-radiative energy transfer from fluorescent emitters (nitrogen vacancy centers) to graphene [2]. Such centers are considered to play a crucial role in future quantum technologies. In addition, we describe the picosecond optoelectronic dynamics in metal-dichalcogenides and an ultrafast helicity control of surface currents in 2D layered topological insulators [3].

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REFERENCES
Overview: US-EU Workshop on 2D Layered Materials and Devices

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The decade long research on graphene since 2004 when it was mechanically isolated from parent graphite has served as a nucleation point for the study of a large number of atomic layers derived from non-graphene two-dimensional (2D) materials. These non-graphene 2D atomic layers include materials such as hexagonal boron nitride (h-BN), transition metal di-chalcogenides, tertiary compounds of carbo-nitrides and complex oxides. Leveraging this substantial and pivotal research on graphene, we are now in the midst of another wave of scientific breakthroughs hinged upon these “beyond” graphene 2D layered materials and their potential for unveiling new fundamental properties and science, and enabling frontier device research. The field of 2D layered materials and devices is accelerating at a rapid pace and significant contributions have been made to the field by researchers in Europe and the United States. The purpose of this workshop is to bring together leading scientists working on graphene and beyond graphene 2D materials and devices from Europe and the United States to help promote future collaborations and address common challenges for this dynamic field. In doing so, it is envisioned that such an interaction should help promote synergistic activities in the future and accelerate research progress. In this talk, an overview of the workshop will be provided that includes a discussion of the workshop goals, and final outcomes that are expected to emerge from the break out discussions and future recommendations.

Electron Transport in the van der Waals Interfaces

Philip Kim
Harvard University, USA

Recent advance of atomically thin vdW materials and their heterostructures provide a new opportunity to realize atomically sharp interfaces in the ultimate quantum limit. By assembling atomically thin van der Waals (vdW) materials, such as hexa boronitride, transition metal chalcogenide and graphene, we can construct novel quantum structures. In this presentation, we will discuss construction and characterization of an atomically thin vertical vdW interfaces. Schottky junction, p-n heterojunction and superconductor-metal junctions based on the vdW assembly of transition metal dichalcogenides and graphene have been realized. Unlike conventional semiconductor heterostructures, charge transport of the devices are found to critically depend on the interlayer recombination process between majority carriers mediated by tunneling across the interface. We demonstrate the enhanced electronic optoelectronic performances in the vdW heterostructures, tuned by applied gate voltages, suggesting that these a few atom thick interfaces may provide a fundamental platform to realize efficient, fast and tunable bipolar electronics, photovoltaics, and optoelectronics. We also observe a modulation of the Andreev reflection probability when Cooper pairs are injected across vdW interface between superconductor and graphene.
“Graphene’s Synthetic Cousins: Silicene and Germanene”

Guy Le Lay
Aix-Marseille Université, CNRS-PIIIM, France

Research on synthetic elemental two-dimensional materials beyond graphene is a very hot topic. Silicene, the silicon counterpart of graphene, has been grown on a silver template in 2012, initially as an epitaxial single layer [1], then as multilayers [2], and the first FETs operating at room temperature based on a silicene channel achieved in 2015 [3,4]. Germanene, alternatively, has been grown on a gold substrate, just in 2014 [5], while efforts are pursued to synthesize stanene (sometimes coined tinene), potentially a 2D topological insulator sustaining the quantum spin Hall effect markedly above room temperature due to the very large spin-orbit interaction in tin.

In this talk, I will review the main advances in this burgeoning field.

“Exploring Pathways towards Heterostacks of Graphene and Hexagonal Boron Nitride”

Jürg Osterwalder
University of Zürich, Zürich, Switzerland

Building heterostacks of 2D materials creates fascinating opportunities for creating novel artificial materials. Most current approaches involve the stacking of exfoliated flakes of microscopic size allowing the fabrication and characterization of individual electronic and optoelectronic devices [1]. Our group explores two different pathways for upscaling the preparation of high-quality graphene and h-BN heterostacks. On one hand, parameters for the subsequent CVD growth of graphene and h-BN single- and multilayers on different single-crystalline metal substrates are investigated by rigorous surface science methodology, exemplified by growth on Cu(111) [2] and Rh(111) substrates. For this purpose, a low-cost photoelectron yield setup was developed for in situ process monitoring [3]. The second approach involves the low-pressure CVD growth of well-defined single-layer h-BN and graphene on single-crystalline metal thin films and subsequent transfer for stacking on arbitrary substrates. For this latter method we have access to large area single-crystalline metal films at the four-inch wafer scale [4, 5]. When quantitative film transfer can be mastered, this will allow the stacking of macroscopic flakes with controlled lattice orientation, the importance of which has recently been demonstrated [6].

“High-Field, Thermal and Energy Properties of 2D Devices and Layers”

Eric Pop
Stanford University, USA

Two-dimensional (2D) materials have unique atomic thinness and weak yet tunable coupling between layers, presenting opportunities for low-power transistors, efficient thermoelectrics, and transparent heat spreaders. I will describe our recent progress in examining high-field transport, transistor scaling, optimized contacts, and thermal measurements in 2D materials and their stacks. We have recently uncovered transport physics at TMD and graphene contacts with metal electrodes, including the roles of metal deposition during fabrication and that of thermoelectric (Peltier) effects during transistor operation. I will also describe our understanding of high-field transport in MoS2 and graphene, including the importance of self-heating effects on various substrates such as SiO2, BN and HfO2. I will describe our thermal measurements in suspended graphene and in graphene devices with dimensions comparable to the electron and phonon mean free paths (~100 nm); the former yield the intrinsic behavior of this material, the latter show quasi-ballistic phonon transport near room temperature. Finally, I will discuss some opportunities for “self-cooling” electronics by leveraging built-in thermoelectric (TE) effects, and for designer thermoelectrics that rely on high Seebeck coefficients and clever stacking of 2D layers, with customized electrical and thermal properties.

“Single Photon Emitters in Exfoliated WSe2 Structures”

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Comprehensive optical micro-spectroscopy studies of thin layers of tungsten diselenide, WSe2, a representative semiconducting dichalcogenide with a bandgap in the visible spectral range, will be presented. Special attention will be focused on observation of the centers, located at the edges of WSe2 flakes transferred onto Si/SiO2 substrates, which, at low temperatures, give rise to sharp emission lines (down to 0.1meV). These narrow emission lines reveal the effect of photon antibunching, the unambiguous attribute of single photon emitters. Optical properties of these emitters and their possible origin will be discussed. A working hypothesis that they are due to nano-sized lateral fragments (nano-flakes) of a WSe2 monolayer, which are apparently formed at the edges of exfoliated flakes (monolayers as well as WSe2 multilayers), will be put forward.

References
A. Arora et al., arXiv:1503.01682.
M. Koperski et al., Nature Nanotechnology, accepted for publication; arXiv:1411.2774.
Some of the most dramatic accomplishments with 2D materials have been enabled by properties that emerge only at the single or few-layer limit and are not found in bulk forms. I will discuss our efforts to elucidate several new and useful emergent properties of monolayer and few-layer materials. Using and developing a variety of atomistic modeling methods, we have predicted that many of the commonly studied single-layer and few-layer transition metal dichalcogenide (TMD) materials (e.g. MoS$_2$) exhibit substantive electromechanical coupling in the form of piezoelectric and flexoelectric-like effects, unlike their bulk parent crystals. I will describe the first recent observations of some of these effects in the laboratory by researchers at Columbia, Georgia Tech, Berkeley and elsewhere.

Single-layers of two-dimensional Mo- and W-dichalcogenide compounds differ from graphene in an important respect: they can potentially exist in more than one crystal structure. Some of these monolayers exhibit hints of a poorly understood structural metal-to-semiconductor transition with the possibility of long metastable lifetimes. If controllable, such a transition could bring an exciting new application space to monolayer materials. We have discovered that mechanical deformations provide a route to switching thermodynamic stability between a semiconducting and a metallic crystal structure in some of these monolayer materials. Our DFT-based calculations reveal that single-layer MoTe$_2$ exhibits a phase boundary at a few percent tensile strain. The potential application space for this work ranges from information and energy storage to electronic and optical electronic devices.

References


“Valley Zeeman Effect of Free and Bound Excitons in WSe₂”

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The existence of two inequivalent valleys in the Brillouin zone of transition metal dichalcogenides represents a pseudo-spin degree of freedom that can be optically addressed using circularly polarized light. In this talk, I will present our recent results demonstrating a Zeeman effect arising from the valley degree of freedom in monolayer WSe₂[1]. We performed low temperature magneto-optical spectroscopy to investigate the exciton and trion resonance in presence of magnetic fields. A splitting of exciton and trion peaks is observed in photoluminescence and differential reflectance only in a magnetic field perpendicular to the sample, growing linearly with the field. The split peaks are circularly polarized with opposite helicities, implying that they stem from opposite valleys. The measured magnetic moment of ~ 4.3 Bohr magnetons for the exciton peak is explained considering excitonic effects on the intracellular (orbital) and intercellular (lattice) contribution to the orbital magnetic moment. The trion magnetic moment is found to be anomalously large, hinting at a different contribution.

In addition to the free exciton peak, we occasionally observe spatially localized, sharp emission peaks with linewidths ~ 120 μeV which are 20 to 100 meV lower than the free exciton resonance, arising from bound excitons [2]. We find an anisotropic magnetic response similar to that of the free exciton peak with split peaks showing opposite helicities at large enough fields. However, the magnetic moment (~ 9 Bohr magnetons) is much larger than that of the free exciton and trion. Our results show that the valley degree of freedom is preserved even in bound excitons making them attractive for optical control of spin-valley degree of freedom in TMDs.

References
“Tunable Exciton-Polaritons in van der Waals Heterostructures”

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Monolayer films of van der Waals crystals of transition metal dichalcogenides (TMDCs) are direct band gap semiconductors exhibiting excitons with large binding energies and small Bohr radius, leading to a high oscillator strength of the exciton optical transition. Here we report fabrication of van der Waals ‘quantum wells’ (QW) made from molybdenum diselenide (MoSe₂) light-emitting layers and hexagonal boron nitride (hBN) barriers. Such heterostructures are embedded in an optical microcavity consisting of a concave and a planar dielectric distributed Bragg reflector (DBR) separated by a tunable micrometer sized gap [1,2]. We observe the strong exciton-photon coupling regime and formation of exciton-polariton states, whose energy can be tuned by changing the gap between the DBR mirrors. Furthermore, we demonstrate that the magnitude of the characteristic anti-crossing between the cavity mode and the exciton states (a Rabi splitting) can be controlled by embedding a multiple-QW structure, containing two MoSe₂ monolayers separated by an hBN barrier. At a temperature of 4K, for a single QW sample the vacuum Rabi splitting of 20 meV is observed for the neutral exciton state, which is increased to 29 meV for the double QW, following closely the \( \sqrt{N_{QW}} \) dependence. An intermediate coupling regime is observed for the charged exciton, where the polariton states are not fully resolved as the Rabi splitting is similar to the charged exciton linewidth. This work opens a new avenue in the field of polaritonics in a new material system of van der Waals crystals.

This talk will discuss the synthesis of large-area, high-quality monolayers of nitrogen-, silicon- and boron-doped graphene sheets on Cu foils using ambient-pressure chemical vapor deposition (AP-CVD). Scanning tunneling microscopy (STM) and spectroscopy (STS) reveal that the defects in the doped graphene samples arrange in different geometrical configurations exhibiting different electronic and magnetic properties. Interestingly, these doped layers could be used as efficient molecular sensors and electronic devices. In addition, the synthesis of hybrid carbon materials consisting of sandwich layers of graphene layers and carbon nanotubes by a self-assembly route will be discussed. These films are energetically stable and could well find important applications as field emission sources, catalytic supports, gas adsorption materials and super capacitors.

Beyond graphene, the synthesis of other 2-Dimensional materials will be described. In particular, we will discuss the synthesis of WS\textsubscript{2} and MoS\textsubscript{2} triangular monolayers, as well as large area films using a high temperature sulfurization of WO\textsubscript{x} clusters deposited on insulating substrates. We will show that depending on the substrate and the sizes of the oxide clusters, various morphologies of layered dichalcogenides could be obtained. In addition, photocurrent measurements on these materials will be presented. Our results indicate that the electrical response strongly depends on the laser photon energy. The excellent response observed to detect different photon wavelengths in MoS\textsubscript{2}, WS\textsubscript{2} and WSe\textsubscript{2} materials, suggest these materials could be used in the fabrication of novel ultrafast photo sensors.

Black phosphorus recently emerged as a promising new 2D material due to its widely tunable and direct bandgap, high carrier mobility and remarkable in-plane anisotropic electrical, optical and phonon properties. It serendipitously bridges the zero-gap graphene and the relatively large-bandgap transition metal dichalcogenides such as molybdenum disulfide (MoS\textsubscript{2}). In this talk, I will first cover the basic properties of few-layer and thin-film black phosphorus, followed by a discussion of recent observation of highly anisotropic robust excitons in monolayer black phosphorus. Finally I will present a few potential applications of black phosphorus such as radio-frequency transistors and wideband photodetectors.
Optoelectronics of 2D Semiconductors and Heterostructures

Xiaodong Xu
University of Washington, USA

Heterostructures comprising different monolayer semiconductors provide a new and highly functional system for fundamental science and device technologies. One such application for this system is in the emerging field of 2D optoelectronics and valleytronics. Here, we demonstrate valley-specific interlayer excitons in monolayer WSe$_2$-MoSe$_2$ vertical heterostructures. By optical pumping, we create coupled spin-valley polarization of interlayer exciton and measure polarization lifetimes of more than 10 nanoseconds. This long-lived polarization enables the visualization of both spin and valley diffusion over several microns, where the spatial pattern of spin-valley polarization evolves from a disk into a ring with increasing exciton density, a manifestation of valley-dependent many-body interactions.

From the First Principles: Defects in 2D, Variability and Electronic Consequences

Boris I. Yakobson
Rice University, Houston, USA

It is of great interest and importance for materials design to uncover, through computational and theoretical modeling, the following relationships: {basic atomic interactions $\rightarrow$ structure/morphology $\rightarrow$ functionality (including electronic)}. I will briefly overview recent examples from our research of low-dimensional materials, where we seem to achieve satisfactory degree of understanding, mostly focusing on 2D graphene [1-4], transition metal disulfides [5-8], phosphorene [9-10].

Phosphorus is one of the most abundant elements preserved in earth, constructing with a fraction of 0.1% of the earth crust. In general, phosphorus has several allotropes including white, red, and black phosphorus. Black phosphorus, though rarely mentioned, is a layered semiconductor and have great potentials in optical and electronic applications. Remarkably, this layered material can be reduced to one single atomic layer in the vertical direction owing to the van der Waals structure, dubbed phosphorene, where the physical properties can be tremendously different from its bulk counterpart and needed to be further explored. In this talk, we trace back to the 100 years research history on black phosphorus from the synthesis to material properties, and extend the topic from black phosphorus to phosphorene. The physical and transport properties are highlighted, aiming at further applications in electronic and optoelectronics devices.

POSTER - ABSTRACTS

“Transition Metal Dichalcogenide (MoS₂, MoSe₂, MoTe₂, WS₂ & WSe₂, as well as alloys thereof) Growth on Dielectric, Ferroelectric, Conducting and Patterned Substrates”

Ludwig Bartels, University of California at Riverside (bartels@ucr.edu)

High-vacuum and CVD-style growth of MoS₂, MoSe₂, MoTe₂, WS₂ & WSe₂ (e.g., Adv. Mat. 26, 1399 (2014)) as well as the corresponding alloys on different substrates (SiO₂/Si, Graphene, ferroelectric LiNbO₃, etc.) is presented. Our large-scale isotropic films are monolayer-thin; their Raman and Photoluminescence signature rivals that of exfoliated single-layer films. We find that in-situ growth on patterned substrates can either be conformal or bridging between substrate features, the latter resulting in natively-suspended material. Gradual composition variation permits tuning of material properties such as bandgap, photoconductive response time, majority charge carriers, etc. A broad range of characterization methods have been applied to our (alloy) films including scanning photocurrent measurements revealing a superlinear photoconductive response, whose native time constant can be tuned over 5 orders of magnitude by composition (Nano Letters DOI: 10.1021/acs.nanolett.5b00190 ). CVD growth on poled LiNbO₃ permits encoding of film pattern in the poling of the substrate. Local poling allows reversible inversion of the majority charge carrier type even in MoS₂ without the need for special gating. Recently, non-contact surface acoustic wave attenuation allowed us to perform measurements of the transport properties of MoS₂ in the absence of electrodes and ensuing Schottky Barrier.
“Dielectric Environmental Effect on Monolayer TMD Band Gaps”

Yong-Sung Kim,1, 2 Santosh KC,3 and Kyeongjae Cho3, *

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Electrons confined in a small structure in vacuum are strongly correlated through the Coulomb interaction weakly screened via the vacuum. In a spatially isolated condensed matter system (e.g., free nanoparticles, nanowires, and atomically thin 2D materials), the quasi-particle renormalization of electrons is known to be large. When a confined system is located in the proximity of dielectric medium as in electronic devices, the Coulomb interaction in the confined system is screened additionally, and the renormalized electronic structures would be strongly modified. We have investigated the environmental dielectric screening effect on the quasi-particle electronic structures of monolayer transition metal dichalcogenide (TMD) semiconductors. The GW quasi-particle band gap of 2.8 eV in an isolated monolayer MoS₂ is largely reduced down to 2.0 eV by the environmental dielectric screening effect. This finding explains the origin of conflicting reports on TMD band gap size, and provides a conceptual understanding to facilitate the integration of TMDs into device structures.

This work was supported by Nano R&D Program in NRF of Korea (Grant No. NRF-2009-0082489), Nano·Material Technology Development Program in NRF of Korea (2012M3A7B4049888), and the Center for Low Energy Systems Technology (LEAST).
“Electrical Transport and Low-frequency Noise in MoS₂ Field-effect Transistors”

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High current $I_{ON}$-$I_{OFF}$ ratio and low magnitude of low-frequency noise (LFN) are essential for efficient field-effect transistors (FETs). This poster describes transport and LFN measurements on mono- to few-layer MoS₂ FET structures with and without top-surface passivation. Temperature dependent measurements on Al₂O₃ top-passivated MoS₂ FETs indicated band-like electrical transport mechanism, while for devices with etched Al₂O₃ layer, a weak temperature dependence of the resistance pointed to a defect mediated transport mechanism. Notably, the top surface passivation significantly reduced the drain current noise. For both passivated and etched devices, the bias dependent LFN at 300 K can be explained by carrier number fluctuation and correlated mobility fluctuation; both related to surface effects. Correlation to the bulk mobility fluctuation model (Hooge’s model) was not observed. Detailed analysis of the gate referred noise voltage power spectral density (PSD) indicated the presence of different trapping states in passivated devices when compared to the etched devices.

In addition, a study on MoS₂ FETs with different channel thicknesses revealed that 4 to 6 layers (L) thick FETs had highest $I_{ON}$-$I_{OFF}$ ratio ($\approx 10^6$). The LFN experiments revealed that the normalized PSD of the drain current was the minimal ($\approx 2 \times 10^{-8}$ Hz⁻¹) for L=6 layers, whereas the noise was maximum for a monolayer FET with normalized PSD $\approx 1.5 \times 10^{-5}$ Hz⁻¹ at 10Hz. Further, LFN for few layer devices satisfied carrier number fluctuation (CNF) model in both weak and strong accumulation regime while thicker devices followed Hooge’s mobility fluctuation (HMF) model in the weak accumulation regime and CNF model in strong accumulation regime respectively. In summary, MoS₂ FETs with 4-6L gave best performance in terms of both transfer characteristics and LFN.

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“Direct Growth of Hexagonal Boron Nitride on Epitaxial Graphene by High-Vacuum Chemical Vapor Deposition”

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This work reports on progress towards direct, epitaxial growth of hexagonal boron nitride (h-BN) on graphene, with the long-range goal of forming graphene/h-BN based vertical tunneling heterostructures. By exposing graphene samples (grown on Si-face SiC) to a low pressure ($\sim 1 \times 10^{-4}$ Torr) of borazine at temperatures exceeding 1000°C, we obtain in-situ low-energy electron diffraction patterns consistent with the presence of many randomly oriented grains of h-BN. We find that increasing the growth temperature leads to the development of a preferential orientation, with the h-BN aligning with the underlying SiC substrate. Atomic-force microscopy and low-energy electron microscopy (LEEM) show triangular crystals exceeding 1 μm in extent. Additionally, using a first-principles method for examining low-energy electron reflectivity spectra, we determine the coverage of h-BN on our samples. We show that our method is sufficiently robust to discriminate between various combinations of numbers of h-BN monolayers (MLs) and graphene MLs based on unique features in their spectra. Prospects for improvement of the h-BN crystallinity, as well as the controlled growth of a specific number of MLs are discussed.

This work was supported by the National Science Foundation and by the Center for Low Energy Systems Technology (LEAST), one of the six SRC STARnet Centers, sponsored by MARCO and DARPA.
A new type of flash memory will be presented that is well suited for two-dimensional (2D) crystal materials, such as graphene. The memory relies on the electrostatic gating of 2D crystals using lithium ions. Although ions are generally avoided in semiconductor device manufacturing, they have gained attention recently in devices such as resistive random access memory (RRAM), where conductive filaments are formed and broken to create states of low and high resistance. The device consists of two graphene layers separated by an ion conductor with source/drain contacts deposited on the top graphene layer. The source/drain are used to sense the presence or absence of ions adjacent to the channel, setting the low and high resistance states. The bottom graphene is a gate, which moves the ions back and forth across the ion conductor. Because the ions physisorb to the graphene without exchanging charge, the wear-out associated with the making and breaking of chemical bonds is eliminated. The memory is nonvolatile because the electrostatic double layer formed by the electrons in the graphene and the cations in the ion conductor is retained when the power is removed. The memory concept will be presented, along with our progress towards the development of nanometer-thick ion conductors. This includes density functional theory (DFT) calculations showing that the molecule-ion pair that satisfies the requirements of the memory is 15-crown-5/Li$^+$. Atomic force and scanning tunneling microscopy measurements show that the ion conductor forms an ordered monolayer on highly ordered pyrolytic graphite (HOPG) and scanning tunneling spectroscopy (STS) indicates that the band gap of the ion conductor is 1.25 eV.

This work was supported in part by the Center for Low Energy Systems Technology (LEAST), one of six SRC STARnet Centers, sponsored by MARCO and DARPA, and NSF grant #ECCS-GOALI-1408425.

“Material Characterization of 2D Layered Crystals for Printed Electronics Applications”

Monica Lugo$^1$, Dalal Fadil$^{1,2}$, Gustavo Lara$^2$, Alberto Delgado$^1$, Christopher Gaytan$^2$, Esteban Escarcega$^1$ and Anupama Kaul$^{1,2}$$^*$

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Carbon based nanomaterials, such as graphene, have been proposed for a wide variety of applications including beyond Si-CMOS architectures, interconnects, field-emission displays, photo-voltaics and nano-electro-mechanical-systems (NEMS) given its remarkable electronic, thermal, mechanical and optical properties. Recently, layered 2D crystals of other materials similar to graphene have been realized which include insulating hexagonal-BN (band gap $\sim 5.5$ eV) and transition metal dichalcogenides that display diverse electronic, optical and mechanical properties. Here we provide some preliminary results on material characterization investigation of some of these 2D layered crystals, specifically MoS$_2$ and graphene which we have dispersed in several solvents, including ethyl cellulose. These solution dispersed 2D crystals have potential applications in printed electronics. Recently, ink jet printing of graphene, has emerged as a promising direction to explore applications, given the unique electronic, optical and mechanical properties of graphene. Although graphene can be used in flexible interconnects, its lack of a bandgap limits functionality and implies that it cannot replace conjugated polymers as the semiconducting material in printed electronic devices. At the same time, the emergence of beyond graphene 2D layered materials has provided more diversity in the range of properties stemming from these materials, where metallic, semi-metallic, semiconducting, insulating, topological, superconducting and thermoelectric behavior is easily accessible. Here we report on the structural, electronic and optical properties of our 2D crystals that have the potential to be integrated into device platforms for printed electronics applications.
We have grown Graphene/BN heterostructures on Co(0001) with precise control of the number BN and graphene layers, and without physical transfer. The direct growth of graphene and BN single and multilayers on suitable substrates without physical transfer is critical toward industrial development of 2D devices. Predicted [1, 2] high performance magnetic tunnel junctions and spin valves also require growth of azimuthally oriented multilayers on ferromagnetic substrates with atomically precise control of layer thickness. We report the formation of macroscopically continuous h-BN(0001) multilayers (1 cm x 1cm) by atomic layer epitaxy (ALE) on Co(0001)[3]. We also report the growth of single and few layer graphene on h-BN(0001) by chemical vapor deposition (CVD) and molecular beam epitaxy (MBE), respectively [4, 5]. LEED measurements indicate azimuthally oriented growth of both BN and graphene layers in registry with the Co(0001) lattice without interfacial oxidation, with BN domains > 300 Å. Photoemission data indicate B:N atomic ratios of 1:1. Growth temperatures < 650 K (BN) and < 800 K (graphene MBE) suggest multiple integration schemes for both spintronics logic and memory.

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“Novel Sensor, Memory and Logic Devices using Two-Dimensional Materials”

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Two-dimensional (2D) materials have been of tremendous interest in the last few years due to their novel electronic and photonic properties and their corresponding potential to realize a wide range of novel devices. This poster describes recent work on novel devices based upon 2D materials for sensing, memory and logic applications. In particular, the low density of states and high mobility in graphene allow the realization of high-Q variable capacitors which can be used to create ultra-compact wireless sensors. In addition, transition metal dichalcogenides (TMDs) are shown to be promising for extremely-low leakage embedded memory applications due to their wide band gap and high effective mass. Furthermore, it is shown that TMD-based heterostructures are promising to realize scalable tunneling field-effect transistors (TFETs) for ultra-low-power logic. Finally, recent results on few-layer black phosphorus MOSFETs with record transconductance suggest that this material is very promising as a platform for high-performance CMOS logic circuits.
“Engineering Contacts for PVD Grown 2D Transition Metal Dichalcogenides Devices”

Michael H. Check, Michael E. McConney, Chris Muratore, Adam Waite, Jian-Jun Hu, Michael Jespersen, Andrey A. Voevodin, Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB, Ohio

“Symmetric 2D Vertical Heterostructure Devices: Simulation and Experiment”

Eric M. Vogel, Georgia Institute of Technology

Since the 1970s, resonant tunneling devices have attracted significant attention for their potential in a variety of applications including multi-valued logic, high frequency radar and communication systems, analog-to-digital conversion and signal processing. Vertical heterostructures consisting of two-dimensional (2D) materials such as graphene, hexagonal boron nitride (h-BN) and transition metal dichalcogenides (TMDs) have a variety of properties which can potentially overcome some of the limitations of epitaxial 3D semiconductor heterostructures. Simulations of 2D heterostructures will be described including how various properties and parameters impact the predicted current-voltage characteristics. Challenges associated with fabricating heterostructures based on large-area and manufacturable materials focusing on graphene-insulator-graphene (GIG) heterostructures will also be presented. Overall, the results provide important insights necessary for future, large-scale manufacturing of resonant and other 2D vertical heterostructure devices.

“Surface and Interfaces for 2D Beyond CMOS Materials”

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A number of 2D materials are under investigation as potential candidates for materials in beyond CMOS applications. In addition to graphene, materials such as transition metal dichalcogenides (TMDs) and phosphorene have been examined for field effect devices with promising results. However, the detailed understanding and control of the interfaces of these materials with dielectrics, contacts, and even the environment requires attention. This talk will present a review of our recent studies of these materials systems in this context using in situ deposition and characterization methods we have developed.
“Dielectric Environmental Effect on Monolayer TMD Band Gaps”
Yong-Sung Kim,1, 2 Santosh KC,3 and Kyeongjae Cho3, *

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Electrons confined in a small structure in vacuum are strongly correlated through the Coulomb interaction weakly screened via the vacuum. In a spatially isolated condensed matter system (e.g., free nanoparticles, nanowires, and atomically thin 2D materials), the quasi-particle renormalization of electrons is known to be large. When a confined system is located in the proximity of dielectric medium as in electronic devices, the Coulomb interaction in the confined system is screened additionally, and the renormalized electronic structures would be strongly modified. We have investigated the environmental dielectric screening effect on the quasi-particle electronic structures of monolayer transition metal dichalcogenide (TMD) semiconductors. The GW quasi-particle band gap of 2.8 eV in an isolated monolayer MoS2 is largely reduced down to 2.0 eV by the environmental dielectric screening effect. This finding explains the origin of conflicting reports on TMD band gap size, and provides a conceptual understanding to facilitate the integration of TMDs into device structures.

This work was supported by Nano R&D Program in NRF of Korea (Grant No. NRF-2009-0082489), Nano·Material Technology Development Program in NRF of Korea (2012M3A7B4049888), and the Center for Low Energy Systems Technology (LEAST).