The Future of Computing

Moderator: Christopher Palmstrøm, University of California, Santa Barbara

3:00pm PCSI-SuA-1 Chiraltronics: Chiral Domain Wall and Anti-skyrmion Data Storage Elements for High Performance Racetrack Memories, Stuart Parkin, Max Planck Institute, Germany

Over the past few years there have been remarkable discoveries in spin-based phenomena that rely on spin-orbit coupling that could spur the development of advanced magnetic memory devices. One of the most exciting of these is Racetrack Memory that stores digital data in the form of the presence or absence of chiral domain walls. Recent discoveries in the emerging field of chiraltronics makes possible the current induced motion of series of chiral domain walls at high speeds that exceed 1 km/s in atomically engineered racetracks. The same type of Dzyaloshinskii-Moriya exchange interactions that stabilize chiral Néel domain walls in such racetracks also enable the formation of topological spin textures such as spin helices and skyrmions. Recently we have discovered magnetic antiskyrmions in a tetragonal Heusler compound, using Lorentz transmission electron microscopy. Such antiskyrmions are potential storage elements in racetrack memories. These recent discoveries in chiraltronics makes Racetrack Memory extremely attractive as a dense, high performance, low energy consuming, non-volatile memory technology that could make computing systems more compact and yet more powerful.


3:40pm PCSI-SuA-9 Neuromorphic Computing, Angel Yanguas-Gil, Argonne National Laboratory

4:20pm PCSI-SuA-17 Panel Discussion I,
Sunday Evening, January 13, 2019

PCSI Room Ballroom South - Session PCSI-SuE

III-V Growth
Moderator: Lincoln J. Lauhon, Northwestern University

7:30pm PCSI-SuE-1 Understanding the Kinetics of III-V Semiconductor Nanowire Growth using in-situ TEM, C Maliaikkal, D Jacobsson, M Tornberg, A Persson, J Johansson, R Wallenberg, Kimberly Thelander, Lund University, Sweden

INVITED

Semiconductor nanowires have emerged as a highly promising technology for next-generation electronics and photonics, in particular due to their potential for forming novel metastable crystal phases, complex alloys and heterostructure combinations not achievable in bulk semiconductors. The most common method of fabricating these structures is the vapor-liquid-solid mechanism, which makes use of a catalytic liquid metal droplet. The development of these materials requires a fundamental understanding of how they form. Since nanowire growth is performed in a vapor phase atmosphere at high temperature, the dynamic processes controlling their formation cannot be directly deduced by analyzing only the final grown nanostructure. As such, the current mechanistic understanding of the synthesis process is insufficient for achieving the promised level of control.

In order to address this challenge, we use in-situ TEM imaging combined with in-situ compositional analysis to study the processes occurring at the interface between the metal droplet and nanowire, and how these control the final structure. Nanowires are grown in a Hitachi HF3300S aberration-corrected environmental TEM connected to a chemical vapor deposition system designed for III-V semiconductor growth. Growth is performed on a SiNx-based MEMS heating chip mounted on a holder with two separate microtubes for supplying the precursor gases. High resolution, high-frame-rate videos enable us to determine the rate at which individual semiconductor bilayers form, along with the interface morphology, catalyst geometry and nanowire crystal structure. The elemental composition of the catalyst is measured by energy dispersive X-ray spectroscopy as a function of the growth parameters. We identify different ‘regimes’ in which growth occurs that can be identified by the composition and structure of the catalyst, and in which different steps in the growth process control the overall formation rate as well as the structure of the material.

8:00pm PCSI-SuE-7 In situ Studies of Surface Morphological Evolution During Indium Nitride Growth by Atomic Layer Epitaxy, Charles R. Eddy Jr., N Nepal, U.S. Naval Research Laboratory; S Rosenberg, American Association for Engineering Education; V Anderson, Sotera Defense Solutions; J Woodward, American Society for Engineering Education; C Wagenbach, Boston University; A Kozen, American Society for Engineering Education; Z Robinson, College at Brockport SUNY; L Nyakiti, Texas A&M University; S Qadri, U.S. Naval Research Laboratory; M Mehl, U.S. Naval Academy; K Ludwig, Boston University; J Hite, U.S. Naval Research Laboratory

Nitride semiconductors have had significant commercial success, but full bandgap engineering of these materials is prohibited by the high temperature growth processes. Recently, we have developed a growth method –low temperature atomic layer epitaxy (ALEp) – that has empirically produced crystalline semiconductor films with properties comparable to those from conventional growth processes, but at roughly half the growth temperature [1,2]. This has eliminated miscibility gaps in ternary III-N semiconductor films and enabled the realization of full bandgap engineering from 0.7 eV to 6.1 eV.

Despite these empirical successes, the fundamental mechanisms involved in ALEp are unknown and the full promise of the method unrealized. To proceed, we use our model of emission built from the atom probe and x-ray data. We find that both composition and polytype play a role in explaining differences in local optical properties, providing a comparison with a non-ALEp thin film.


8:05pm PCSI-SuE-8 Growth Strategies for Modifying Heterovalent Interfaces, Kirstin Alberi, K Park, National Renewable Energy Laboratory

Integration of dissimilar semiconductor materials is becoming an increasingly important pathway for pushing the boundaries of device performance by expanding the options for material selection. The major challenge that must be overcome is the formation of interfaces between two materials with different valences. Charge imbalances arising at interfaces between conventional semiconductors are often alleviated through re-distribution of atoms, which can lead to intermixing-induced degradation of the adjoining layers.

Here, we show that a combination of elemental treatments combined with UV photon exposure can be used to tailor the properties of model ZnSe/GaAs interfaces formed by molecular beam epitaxy. X-ray diffraction and photoluminescence were used to assess the interface roughness and degree of intermixing. Treatment of an As-terminated GaAs surface with UV light and a Se flux results in both an abrupt interface and passivation of the underlying GaAs epilayer. We propose that this improvement over interfaces grown under dark conditions and treatment with a Zn flux is triggered by light-induced desorption of As atoms followed by enhanced Ga-Se bond formation [1]. Thus, the combination of light and elemental treatment during interface initiation offers a highly tunable approach to significantly alter interface properties.

10:00pm PCSI-SuE-9 InAs QD Formation on GaAs(110) by Bi-surfactants, W Martyanov, Technische Universität Berlin, Germany; R Lewis, Paul-Drude-Institut für Festkörperelektronik, Germany; H Jansen, P Farin, R Ziellinski, C Schulze, A Lenz, Technische Universität Berlin, Germany; L Geelhaar, Paul-Drude-Institut für Festkörperelektronik, Germany; Holger Eisele, Technische Universität Berlin, Germany

Nanowire core-shell heterostructures are promising candidates for developing on-chip photonic light sources. Here we investigate the emission characteristics of InGaAs quantum wells grown on GaAs nanowires and the dependence on nanowire polytype, indium mole fraction, quantum well morphology (width), and strain. We have measured each of these structural characteristics through correlated atom probe tomography and x-ray nanodiffraction. Correlated cathodoluminescence was used to map local optical properties, providing a comparison with a model of emission built from the atom probe and x-ray analyses. We find that both composition and polytype play a role in explaining differences in emission between zinc blende and wurzite regions.

Author for correspondence: lauhon@northwestern.edu
Progress in the emergent field of topological superconductivity relies on synthesis of new material combining superconductivity, low density, and spin-orbit coupling. Theory indicates that the interface between a one-dimensional semiconductor with strong SOC and a superconductor hosts Majorana-modes with nontrivial topological properties. We present our recent developments in materials synthesis and growth of density-controlled surface 2D InAs quantum wells with epitaxial superconducting Aluminum. These developments have led to unprecedented control over proximity effect in semiconductors where electron densities can be tuned using a gate voltage. We demonstrate Josephson junctions with IV characteristic indicating highly transparent contacts. We focus on multiterminal junctions and superconducting quantum interference device (SQUID) geometry to investigate the subtle interplay between supercurrents and spin orbit interaction in these materials. The amplitude and shape of current phase plot is varied as critical currents in each arm are independently controlled using gate-tunable junctions. The data can be well described using solution of Bogoliubov–de Gennes equation for our SQUID junctions. We discuss potential applications in gate-based qubits as well as exploring topological superconductivity for computation.
Monday, January 14, 2019

PCSI
Room Ballroom South - Session PCSI-1MoM
2D Plasmonics
Moderator: Anders Mikkelsen, Lund University, Sweden

8:30am PCSI-1MoM-1 Controlling Light at the Atomic Scale with 2D Polaritons, Javier Garcia de Abajo, ICF0-Institut de Ciencies Fotoniques, Av. Carl F. Gauss 3, 08860 Castelldefels (Barcelona), Spain INVITED
Two-dimensional materials have been recently shown to host robust polaritonic modes, ranging from plasmons in highly doped graphene to excitons in transition metal dichalcogenides. The electromagnetic behavior of these modes can be well understood in terms of an effective surface conductivity, in which we can capture their strong dependence on temperature and external static electric and magnetic fields. In this talk, I will overview the general characteristics of the optical response of these materials, which we can understand in terms of simple theoretical descriptions. We will also cover more sophisticated descriptions, aiming at exploring genuinely quantum-mechanical effects. We will further overview recent advances in ultrafast optical response and nonlinear optics, as well as the potential application of these materials for quantum-optics and optical sensing.

9:05am PCSI-1MoM-8 An Optical transformer-based Campanile Near-field Probe on an AFM Cantilever, K Le, aBeam Technologies; S Blilent, Lawrence Berkeley National Lab; C Pina-Hernandez, aBeam Technologies; S Cabrini, Lawrence Berkeley National Lab; Keiko Munechika, aBeam Technologies
Near-field scanning optical microscopy (NSOM) is a powerful and unique approach to characterize the chemical, physical and biochemical properties of materials with the nanometer scale resolution in real-time. NSOM has so far played only a niche role as characterization technique due to one main bottleneck: the need of reliable, efficient, and broadband near-field probes. An optical transformer-based Campanile near-field probes are a novel class of nano-optical tips, which proved to operate extremely reliably, can be employed by non-experts, are completely independent of the substrate type, and combine superior performance in terms of spatial resolution, near-field enhancement, bandwidth, and signal to noise ratio. Since the invention of the probes, the tips have been successfully used for multidimensional spectroscopic imaging of nanostructures with nanoscale resolution, providing so far in-accessible insights into optoelectronic process. The original probes are fabricated on top of an optical fiber. Our aim is to develop the fabrication technology to incorporate the Campanile optical transformer into a standard atomic force microscopy (AFM) platform as a novel class of NSOM probes.

We report a realization of Campanile near-field scanning optical probe on an AFM platform. The fabrication process was based on standard microolithography techniques allowing a straightforward production of multiple cantilevers on a wafer scale. Figure 1 shows a scanning electron micrograph (SEM) image of an optical transformer on a cantilever. The measured resonance frequencies of the AFM cantilevers are in excellent agreement with the optical calculations over different cantilevers as shown in Figure 2, which justifies our characterization. This work paves the way for low cost and reproducible manufacturing of near-field probes suitable for high-resolution hyperspectral imaging.

9:10am PCSI-1MoM-9 Localized Surface Curvature Artifacts in Gap-mode Tip-enhanced Nanospectroscopy, Darya Stepanchishova, Tomsk Polytechnical University, Russia
Tip-enhanced Raman spectroscopy (TERS) allows for chemical analysis to exceed the limit of light diffraction and to reach nanoscale spatial resolution. The high-spatial sensitivity is provided by the metal substrate in the so-called gap-mode TERS. However, in this case, the connection between the tip and the sample could lead to distortions in the image of the nanostructure during visualization. The purpose of this work is to provide a generalized view of such image artifacts in TERS imaging and to find out whether these effects occur and to what extent. We used ultrathin molecular layers and self-assembly monolayers as Raman-active probes deposited on Au and Si films and Au nanostructures. In addition to the 6-fold amplification of the Raman signal, we found that the sample curvature in gap-mode induces imaging artifacts visible as distortions in the electromagnetic field distribution.

Our results show that the use of gap-mode significantly increases the signal strength, but that at the same time, the sample curvature makes an impact to the TERS image contrast which was not considered until now. Beyond metal nanoparticles functionalized with organic molecules, our conclusions impact the nanoscale chemical visualization of molecular and inorganic systems using vibrational spectroscopy.

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PCSI
Room Ballroom South - Session PCSI-2MoM
Atomic Layer Deposition & Etching I
Moderator: Anders Mikkelsen, Lund University, Sweden

9:15am PCSI-2MoM-10 How Chemistry Drives Microstructure: Probing the Structure of sub-nm ALD Materials using in-situ FTIR and Synchrotron Techniques, Angel Yanguas-Gil, Argonne National Laboratory INVITED
Atomic layer deposition is a thin film technique that is well known for its ability to coat high surface area materials.[1] However, it is also an ideal model system to understand how surface interactions drive the growth and evolution of microstructure of materials at the nanoscale: processes based on self-limited precursor-surface interactions are ideally suited for multimodal characterization, allowing the design of experiments and reactors that are optimized for specific characterization techniques. To complement in-situ techniques such as quartz crystal microbalance, FTIR, or XPS, which focus primarily on the surface chemistry and electronic properties of materials, we have developed a modular in-situ reactor at the Advanced Photon Source that gives us access to multiple techniques that can provide detailed microstructural information, including X-ray scattering, XAFS, and PDF. [2]

In this talk I will show how we can apply these techniques to understand the interplay between surface chemistry and microstructure. I will focus on two examples: the synthesis of materials with a controlled distribution of dopants, and the evolution of microstructure from isolated cations to a bulk-like structure. The primary target of our research has been oxide-based materials such as ZnO, In2O3, MgO, HfO2, and nanolaminates.[2-4] However, recently we have expanded to other materials systems, including hybrid organic/inorganic systems and 2D materials such as MoS2.[5]

Overall, the development of new in-situ characterization tools at synchrotron radiation facilities worldwide is going to be an enabling capability that will help us understand the driving forces behind the emergence of crystallinity and the control of microstructure at low temperatures.


9:45am PCSI-2MoM-16 Mechanism of Hydrogen Plasma Modified ALD Growth of Metal-enriched Oxides Studied by In-Situ Mass Spectrometry, Thomas Larrabee, S Prokes, Naval Research Laboratory
Modifying atomic layer deposition (ALD) growth by inserting argon/hydrogen plasma steps has been shown to alter the stoichiometry of oxides, driving metal-enriched films and lower oxidation states. Altering oxide stoichiometry is useful for changing the electrical conductivity, optical properties, bandgap, and other device characteristics; often inaccessible from typical ALD growth. It has been unclear what the mechanism of the plasma-surface reactions and modifications to standard chemical (or “thermal”) ALD growth has been in these processes, however. To elucidate this mechanism, a quadrupole mass spectrometer has been used to examine both reactant and product gas species during the ALD and plasma-modified ALD reactions of ZnO growth from diethyl zinc (DEZ), water, and H2/Ar plasmas.

Comparison was made between thermal reactions, inserting H2/Ar plasma after the metal precursor step, after the oxidant step, between sequential metal precursor steps before the oxidant step, and of argon-only plasma between sequential metal steps. Evidence for a mechanism involving metal-organic ligand desorption and further reaction with the plasma upon H2/Ar plasma exposure is to be presented. No evidence demonstrating terminal oxygen atoms from the growing film, either by O2 or H2O gas evolution was found. Zinc metal enriching in ZnO growth occurs when the H2/Ar plasma is inserted between sequential DEZ steps before the water steps. When the ethyl-terminated surface (after DEZ reaction) is exposed to plasma, primarily a small amount of methane (M/Z = 16) is produced, with
a trace of ethane (M/Z = 28). This is due to ethane desorption and fast reaction with the large excess of hydrogen radicals from the plasma, cracking ethane to methane. After desorption of ethyl ligands, sites open up for additional adsorption of Zn in the second DEZ step. Plasmas containing hydrogen are required, as no ethane nor methane was observed with argon-only plasma.

To verify the generality of this mechanism for plasma-modified ALD using hydrogen plasmas to metal enrich ALD-grown oxides, additional modified oxide materials will also be presented (i.e. NbO2 to Nb2O5, etc.).

9:50am PCSI-2MoM-17 In Situ Investigation of Doping of 2D Semiconductors During Atomic Layer Deposition of Dielectrics, Michael Moody, J Shang, J Chen, A Henning, T Lohr, T Marks, L Lauhon, Northwestern University

The sensitivity of ultrathin and 2-dimensional (2D) semiconductors to the surrounding environment provides a key opportunity for control of material and device behavior. Especially as substitutional dopants may be difficult to control and lead to increased scattering, adlayers are a promising approach to tuning the Fermi level in 2D semiconductors [1]. Despite the growing body of results using oxide dielectrics to this end, there is a lack of mechanistic investigation and understanding of scope and limitations.

In this talk, we build on results using atomic layer deposition of a tunable oxide to dope MoS2 [2], and investigate mechanisms of growth and doping via in situ electrical measurements. Using a modified atomic layer deposition (ALD) reactor, we can measure field-effect transistors during dielectric growth at temperatures up to 300°C. As well as being more efficient than ex situ measurements for some studies (e.g. carrier concentration vs. thickness [3]), it enables otherwise-impossible observation of dynamics and changes with each half-cycle of deposition. We are therefore also positioned to learn about growth and reactivity. The first and to date only other such in situ electrical measurements identified that physisorption of ozone promotes dielectric growth on graphene [4]. We further observe observable ozone doping of the crystallized number of SnSe layers increases and the growth rate of the main layer on the nucleated seed layer (0.10 nm/cycle) was 50% higher than that on the amorphous seed layer (0.10 nm/cycle). As a result, the root-mean-square roughness of the main layer increased from 0.5 nm on the amorphous seed layer to 2.1 nm on the mixed phase (amorphous and crystalline) seed layer, where the main layer growth on the crystallized portion was higher than that on remaining amorphous portion. When the seed layer was well crystallized, the main layer roughness decreased again to 1.0 nm by the uniformly high growth rate across the entire surface. The dielectric constants of the main layers increased from 20 to 100 when the annealing temperature of the seed layer increased from 450 to 650 °C due to the improvement of the film crystallinity.

PCSI
Room Ballroom South - Session PCSI-3MoM
Topological Materials
Moderator: Javad Shabani, New York University

11:00am PCSI-3MoM-31 Topological Heterostructures by Molecular Beam Epitaxy, Susanne Stemmer, University of California, Santa Barbara

Topology, both in real space and in reciprocal space, has emerged as a new design principle for materials that can host a wealth of novel properties. Interfaces and heterostructures with topological materials offer opportunities to control and manipulate their electronic states and associated phenomena, for example, via electric field effect, strain, or symmetry breaking. In this presentation, we will discuss recent progress in the growth of thin films of the three-dimensional Dirac semimetal Cd3As2 by molecular beam epitaxy. We show that high-mobility, epitaxial Cd3As2 films can be grown and discuss some of the phenomena that can be observed, such as an unusually large negative magnetoresistance under parallel electric and magnetic fields. The heterostructures allow for experimental tests of theoretically predicted transitions between topological states by manipulating parameters, such as confinement and film strain. For example, as the film thickness is reduced, a band gap opens in the bulk Dirac electronic states and we observe a quantum Hall effect. Using electric field gating and Landau level spectroscopy, we demonstrate the Dirac dispersion of these two-dimensional states.

11:30am PCSI-3MoM-37 Structural Distortions and Surface/Bulk Competition in quasi-2D SnSe-TiSe: Nanolayered Heterostructures, Sage Bouers, National Renewable Energy Laboratory; D Hamann, D Merrill, J Otto, M Esters, University of Oregon; D Roberts, University of Colorado at Boulder; A Zokutayev, National Renewable Energy Laboratory; D Johnson, University of Oregon

Low dimensional materials and their heterostructures are becoming increasingly important due to their emergent properties not observed in bulk analogues. As the fraction of surface or interface atoms become comparable to the bulk, so too do their contributions to the free energy. Since the most stable interface structure does not necessarily agree with the most stable bulk structure, competition between structures can cause size-dependent distortions or phase transitions. These structural behaviors can fundamentally alter the electronic environment, significantly affecting the material properties.

I will present on multilayer heterostructures formed by self-assembly of designed precursors. This will focus on a system containing quasi-2D layers of SnSe interleaved with TiSe2, which exhibits size-dependent distortions and transport properties. When a single bilayer of SnSe is present all atoms reside at a TiSe interface, templating is observed and long-range 3-dimensional order is established in the heterostructure.[1] However, as the number of SnSe layers increases and “bulk” atoms are introduced, distortions, additional structures, and new stacking sequences are observed.[2] These findings are corroborated by DFT calculations. The changing SnSe structure has profound effects on the composite transport properties with a shift in carrier type, as shown by Seebeck coefficient and Hall measurements.

This designed precursor approach has also been used to study thermoelectric enhancement[3] and quantum phase transitions[4] as a function of layer thickness in other selenides. Working extending this approach to sulfides is currently underway at NREL, and I will briefly present our initial results synthesizing similar heterostructures via combinatorial sputter deposition.

11:35am PCSI-3MoM-38 Gold-gold Dimer Buckling and Electronic Structure of Epitaxial LaAuSb Films, Patrick Strohbeen, D Du, C Zhang, E Shourov, University of Wisconsin-Madison; F Rodalakis, J McChesney, Argonne National Laboratory; P Voyles, J Kawasaki, University of Wisconsin-Madison

Recently, a new subset of hexagonal Heuslers with composition LnAuSb (Ln = La-Nd, Sm) was predicted to exist and shown to be stable in bulk polycrystalline samples. These compounds contain 19 electrons per formula unit, typically thought to be unstable through traditional electron counting rules, however these compounds have been predicted to be stabilized through by locallyizing the 19th electron in Au-Au dimer bonds. Of these new phases, LaAuSb was also predicted through bandstructure calculations to be a Topological Dirac Semimetal (TDS). Here, we will (1) investigate this unique crystal structure and (2) study the electronic properties and structure of single phase epitaxial LaAuSb thin films.

In the original study, LaAuSb was grown in a bulk crystal, however it was both polycrystalline and full of impurity phases and thus it did not lend itself well to study. Here we use molecular beam epitaxy (MBE) to grow single crystalline thin films on c-plane sapphire to investigate the proposed "dimerized" structure. Growth was monitored in situ by reflection high energy electron diffraction (RHEED) in which the resultant film patterns were streaky and well-resolved Kikuchi lines were observed (Fig. 1a,b), indicating the well-ordered and relatively flat surface of the film. Strong RHEED oscillations were observed throughout growth as well as Kiessig fringes (Fig. 1d,e) which is also consistent with a layer-by-layer growth mode resulting in a smooth surface and substrate/film interface. Magnetotransport measurements were conducted and show the expected metallic behavior with a residual resistivity ratio (RRR) of 2.25 (Fig. 1f). The peak can be attributed to the allowed intravalence band transitions from the (Γ) valence band to the Γheavy hole valence band and/or interband transitions from the (Γ) to the Γheavy hole conduction band. Possible sources for the strength of the peak, and its temperature dependence will be discussed. We would like to thank Dr. Arnold M. Kiefer and Stephanie Chastang for providing us the strained α-Sn samples.

Acknowledgement: this work was supported by a grant from the Army Research Office, W911NF-17-1-0254

Monday Morning, January 14, 2019

11:40am PCSI-3MoM-39 MBE Growth of CdAs on GaAs(001) Substrates, Anthony Rice, K Alberi, National Renewable Energy Laboratory

The Dirac semimetal CdAs has become a useful material in the scientific community, as it provides access to a variety of interesting phenomena ranging from topological superconductivity to massless Dirac fermions. It is also potentially useful for energy-related applications due to its high electron mobility and large phonon-phonon scattering. Both single crystal and thin film synthesis has been achieved, however thin film research to date has been confined to non-traditional substrates, such as mica [1], or zinc blende [2] orientations, which hinder the use of conventional analytical techniques. Here, we explore the use of a II-VI-Te/GaAs(001) platform to support CdAs. CdTe growth directly on GaAs(001) results in a (111) orientation due to the large lattice mismatch (14.6%), as shown by X-ray diffraction (XRD). A high temperature anneal prior to CdTe growth, resulting in a Ga-rich surface reconstruction, further improves the interface and resulting film morphology. Atomic force microscopy reveals film roughness comparable to CdTe structures on GaAs(111). Growth of CdAs on this platform is explored and compared to similar films on GaAs(111) substrates.

and X-PEEM results could be obtained. By taking advantage of the small spot capability of the KREIOS 150 meaningful band structure data has been recorded on such patchy samples.

Acknowledgements: We thank Yu. Dedkov (University of Shanghai, China) and M. Fonin (University Konstanz) for providing beamtime and samples for the measurements with KREIOS 150 at BESSY II.

11:55am PCSI-4MoM-42 Investigating Relative Binding Strengths of Various Dye Attachment Chemistries at the Titania-Dye Interface in Dye-Sensitized Solar Cells, Gregory Smith, B Harvey, J Placzek, Angelo State University

Dye-sensitized solar cells (DSSC) continue to be a promising area of research in our society’s quest for clean and renewable energy. Typically, in these solar cells light is harvested by a dye molecule which is covalently bound to a mesoporous semiconducting material, most commonly titania. The excited electron is injected into the semiconductor and moves down to the electrode. One of the most important parts of these solar cells is the interface between the dye and the semiconductor. Optimally, the bond between dye and semiconductor should be strong, yet allow for rapid electron transport from excited dye to semiconductor. The most common chemistry for this attachment is with one or more carboxylate groups. There is a surprising lack of information about the performance of other chemistries in the literature, particularly experimental evidence. Some theoretical calculations have been performed¹, but it would be very useful to have a library of the experimental performance of various attachment chemistries that could be used when considering specific dyes or in the synthesis of new dye molecules.

Here, we discuss a systematic method to compare the strength of the attachment of different chemistries to titania surfaces. To be able to directly compare chemistries, a model set of molecules were used, each 18 carbons in length capped with the group being studied. These molecules were used to form a self-assembled monolayer on a flat titania surface, then exposed to a typical solvent used in DSSCs at a slightly elevated temperature for 24 hours. The quality of the monolayer was measured before and after exposure using goniometry and ellipsometry. Table 1 shows the amount of degradation seen in each group studied. A description of the method, a comparison of the results, and how the results compare to previous theoretical studies will be included in discussion.

<table>
<thead>
<tr>
<th>Terminal group:</th>
<th>Carboxyl</th>
<th>Thiol</th>
<th>Silane</th>
<th>Phosphonic acid</th>
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<tr>
<td>Degradation:</td>
<td>15.7 %</td>
<td>53.9 %</td>
<td>33.2 %</td>
<td>38.1 %</td>
</tr>
</tbody>
</table>

Table 1. Degradation of each monolayer after exposure to ethanol at 30°C for 24 hours.


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Monday Afternoon, January 14, 2019

PCSI
Room Ballroom South - Session PCSI-1MoA

Device Interface Characterization

Moderator: Kimberly Thelander, Lund University

2:00pm PCSI-1MoA-1 Sequential and In-Situ Atom Probe Tomography and Optical Spectroscopy on Single Luminiscent Nanoscale Objects, Lorenzo Rigutti, University of Rouen Normandie, France INVITED

Correlating two or more microscopy and spectroscopy techniques on the same nanoscale object may yield an amount of information difficult to achieve by other means. In this contribution, we present selected studies of micro-photoluminescence (µ-PL), high-resolution scanning transmission electron microscopy (HR-STEM) and laser-assisted atom probe tomography (APT) performed sequentially on single nano-objects containing quantum confined systems based on III-V and II-VI materials. This approach can be applied to the study of heterostructure interface definition, presence of extended defects such as stacking faults or dislocations, carrier localization and optical emission in quantum confined systems [1-4]. Furthermore, the use of complementary techniques may be extremely helpful for a correct interpretation of atom probe results and for understanding its limitations [3,5]. Finally, we will show that the study of PL in situ in an atom probe opens up novel possibilities, such as the discrimination - with a spatial resolution beyond the diffraction limit - of the optical signal of two quantum wells (QWs) and the manipulation of the optical signal of color centers by the application of an electrostatically-induced stress [6].


2:30pm PCSI-1MoA-7 The Three-dimensional Shape of Antiphase Domains in GaP on Si(001), Pascal Farin, Technische Universität Berlin, Germany

The integration of III-V semiconductors on Si(001) has been a long standing research aim to lower the cost of optoelectronic devices and simultaneously improve their performance. As the lattice mismatch between Si and GaP is smaller than 4%, this particular III-V semiconductor is used preferentially. However, due to charged, three-dimensional defects called antiphase domains (APDs) in GaP arising at the interface, its integration has proven to be quite challenging. While the search for growth conditions to avoid pronounced formation of these defects has been successful, the exact shape of the remaining ones is not yet fully understood.

In this work, APDs in GaP on Si(001) are investigated by means of transmission electron microscopy (TEM) and cross-sectional scanning tunneling microscopy (XSTM), two methods that offer unique insight into the appearance of APDs’ cross sections due to their high surface sensitivity and resolution. The progression of the cross sections of the antiphase boundaries (short: antiphase boundaries) that separate the crystal’s mainphase from the antiphase could be analyzed all the way down to the atomic level, allowing for an identification of the individual crystal planes along which the antiphase boundaries form. The accurate analysis of their progression by means of XSTM is illustrated by Fig. 1. After a thorough investigation of the antiphase boundaries’ appearances on plane-view TEM and on the (110) and the (1-10) cleavage planes by means of XSTM, it has been possible to develop a true-to-scale, three-dimensional model of antiphase domains.

This project was supported by BMBF "MehrSi 03SF0525C", and by DFG through SFB 1083 and LE 3317/1-2.

2:35pm PCSI-1MoA-8 Atom Probe Tomography of GaN Vertical Power Diodes: Impurity Distribution near Regrowth Interfaces, Alexander Chang, Northwestern University; M Nami, B Li, J Han, Yale University; L Lauhon, Northwestern University

GaN has demonstrated its utility in lighting and RF application and are being considered as the next generations of vertical power devices. However, high leakage currents, current crowding followed by premature breakdown, and degradation of the device[1] have hindered the GaN technology from entering the market. For nonplanar vertical power diodes, active regions of the device are formed through ex-situ processes, e.g. regrowth and selective area growth. Therefore, precise control of intentional and unintentional impurity incorporation near these interfaces is essential for achieving high performance devices[2]. Analysis of the 3D spatial distribution and concentration of solute impurity atoms can be difficult, especially for nonplanar interfaces; thus, tomographic analysis becomes necessary. We describe atom probe tomography (APT) characterization of planar n/n and p/n GaN homojunctions with emphasis on detection sensitivity of dopants.

GaN homojunctions were grown by metal-organic chemical vapor deposition at Yale University, and analyzed using APT at Northwestern University. n-GaN templates were exposed to air prior to the regrowth of n-GaN or p-GaN to test subsequent cleaning procedures, and APT detection limits for impurities in GaN substrates and planar regrowth were analyzed by comparison with secondary ion mass spectroscopy (SIMS). Si impurities were observed with a surface density of 10^{15} cm^{-2} for both n/n and p/n homojunctions and attributed to contamination from reactor parts and air. However, detection of Si in GaN using APT was limited due to the overlapping 28Si and 29Si mass to charge ratios. The detection limits of other intentional and unintentional impurities in APT varied from 10^{12} to 10^{14} cm^{-3}, depending on the peak positions relative to the Ga and N ion thermal tails. Analysis on spatial distribution of p-type dopant atoms did not reveal any evidence of clustering. Within the reconstructed APT data, the location of the regrowth interface of n/n homojunction was identified by spatial variations in charge states of evaporated Ga ions (Ga CSR). Although noticeable fluctuations in Ga CSR also coincided with the p/n homojunction, no clear correlation between Ga CSR and Mg concentration was observed. We will discuss efforts to extract the built-in field near p/n junctions and correlate with dopant concentrations.


2:40pm PCSI-1MoA-9 Surface/Subsurface Identification and Control of GaO_{2}, Native Point Defects, Hantian Gao, S Muralidharan, N Pronin, M Karim, S White, T Asel, G Foster, S Krishnamoorthy, S Rajan, L Cao, The Ohio State University; M Higashiwaki, National Institute of Information Communications Technology, H Vonesch, M Grundmann, Universität Leipzig, Germany; H Zhao, The Ohio State University; D Look, Wright State University; L Brillson, The Ohio State University

GaO_{2} has been considered a promising material for next generation high power devices due to its wide band gap enabling very high breakdown fields and n-type doping ranging from intrinsic to degenerate, both features of which lead to numerous solid-state electronic applications. However, surface/subsurface plays an important role in electronic applications of such material. Particularly, native point defects at surface/subsurface remain relatively unexplored. We used two surface sensitive techniques, depth-resolved cathodoluminescence spectroscopy and surface photovoltage spectroscopy to measure the optical signatures related to native point defects at surface/subsurface of GaO_{2}. With near-surface treatments including ion implantation, annealing, and neutron irradiation on β-GaO_{2} grown by different methods, the near-surface sensitivity and depth resolution of these optical techniques enabled us to identify spectral changes associated with removing or creating these defects up to 180 nm below the material surface. This leads to measurement, identification, and control of one oxygen vacancy-related and two gallium vacancy – related energy levels in the β-GaO_{2} band gap. The combined near-surface detection and processing of GaO_{2} suggests an avenue for identifying the physical nature and controlling the density of native point defects in this and other semiconductors at surface and subsurface.


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2:45pm PCSI-1MoA-10 Electrically Detected Magnetic Resonance Study of Leakage Currents in a-Si:H, Ryan Waskiewicz, L Lenahan, Pennsylvania State University; S King, Intel Corp.

Electronic transport in dielectric thin films are important concerns in semiconductor device technology. We have initiated a study of the defects involved in electron transport through a-Si:H thin films of various stoichiometries utilizing electrically detected magnetic resonance (EDMR) measurements at multiple frequencies. The primary defect responsible for
Monday Afternoon, January 14, 2019

PCSI Room Ballroom South - Session PCSI-2MoA

Spectroscopy of 2D Materials

Moderator: Kimberly Thelander, Lund University

2:55pm PCSI-2MoA-12 Light Matter Interaction in Tunable 2D Materials and Artificial van der Waals Solids, Ursula Wurstbauer, University of Münster, Germany

Atomically thin two-dimensional layered materials receive great interest because of their unique properties. Particularly, monolayers of semiconducting transition metal dichalcogenides (SC-TMDs), such as MoS₂, excel due to their strong light-matter interaction that is dominated by exciton phenomena [1-3]. Key to the integration of SC-TDM and related artificial van der Waals solids into circuits is the possibility to tune and engineer their properties on demand and on-chip e.g. by defects, dielectric environment or doping [4-7].

We apply inelastic light scattering together with emission, absorption and transport measurements to study the manifold coupling mechanism in van der Waals hetero- and hybrid structures. We introduce the influence of the dielectric environment, the charge carrier density as well as defects on the optical properties of these atomically thin materials and discuss consequences for their integration into optoelectronic circuits [8]. Moreover, optical properties of direct and indirect interlayer excitons in van der Waals heterostructures are addressed.

We acknowledge the financial support by the Deutsche Forschungsgemeinschaft (DFG) via excellence cluster Nanosystems Initiative Munich (NIM) as well as DFG project WU 637/4-1.


3:25pm PCSI-2MoA-18 Ultrafast Enhancement of Interfacial Exchange Coupling in Ferromagnetic CoFeAl/(Ga,Mn)As Bilayer, Gunter Luepke, College of William & Mary

Fast spin manipulation in low-dimensional magnetic heterostructures, where magnetic interactions between different materials often define the functionality of devices, is a key issue in the development of ultrafast spintronics. Although recently developed optical approaches such as ultrafast spin-transfer and spin-orbit torques open new pathways to fast spin manipulation, these processes do not utilize the unique possibilities offered by interfacial magnetic coupling effects in ferromagnetic multilayer systems. Here, we experimentally demonstrate ultrafast photoenhanced interfacial exchange interactions in the ferromagnetic CoFeAl/(Ga,Mn)As system at low laser fluence levels [1]. The excitation efficiency is 30-40 times higher than without the (Ga,Mn)As layer due to p-d exchange interaction between photoexcited holes and Mn spins (Fig. 1). The coherent spin precessions persist to room temperature, indicating that proximity-induced ferromagnetism plays a key role in the optical excitation mechanism. The results highlight the importance of considering the range of interfacial exchange interactions in low-dimensional heterostructures and how these magnetic coupling effects can be utilized for ultrafast, low-power spin manipulation.

PCSI Room Ballroom South - Session PCSI-3MoA

Magnetism in 2D Materials and Interfaces

Moderator: Anders Mikkelsen, Lund University, Sweden

4:30pm PCSI-3MoA-31 Magnetism in Monolayer Transition Metal Dichalcogenides, Matthias Batzill, University of South Florida

Van der Waals heterostructures hold the promise of combining materials with only weak interlayer interaction. This could allow integration of materials with diverse properties and minimize the influences of chemical interface interactions on materials and device properties. Of particular interest is the integration of magnetic materials in such van der Waals...
heterostructures. Although it has been recently demonstrated that ferromagnetism may be preserved down to the monolayer limit, there exists no known layered van der Waals material with Curie temperatures close to room temperature—which is a pre-requisite for most applications. Thus there has been excitement by theoretical (DFT) predictions of high Curie temperature ferromagnetism in monolayer materials such as VSe₂, a material that is known to be paramagnetic in bulk-form. In addition, there exist increasing evidence of dilute magnetic semiconductors (DMS) in van der Waals materials. In this presentation, we illustrate direct growth of VSe₂ monolayers on van der Waals substrates (Fig. 1) and demonstrate that these (sub)monolayers indeed exhibit ferromagnetic properties at above room temperature [1], while multilayers exhibit strongly suppressed magnetization (Fig. 2). Recent angle resolved photoemission spectroscopy (ARPES) characterization, however, indicate that VSe₂ monolayers do not exhibit spin-split bands as predicted by DFT. In this talk we discuss possible alternative explanations for the observed magnetism. Moreover, we show evidence for magnetic coupling between monolayer VSe₂ and a van der Waals substrate, which gives rise to an exchange bias that can be measured by magnetometry. Finally, we discuss an alternative approach to induce magnetism in 2D materials. Specifically, we show the formation of DMS by incorporation of magnetic impurities (Fig. 3) by a novel doping mechanism [2] in MoTe₂.


5:00pm PCSI-3MoA-37 Epitaxial Growth and STM Characterization of 2D Magnet MnSe₂ and VSe₂, Tiancong Zhu, The Ohio State University; D’O’Hara, University of California, Riverside, J Repicky, J Cobbert, J Gupta, The Ohio State University; R Kowalski, Ohio State University-Columbus

Magnetism in 2D materials is a fascinating topic. Although extensively studied theoretically, the experimental realization of 2D magnets was not achieved until 2017 [1, 2]. Being only a few atoms thick, the high surface to volume ratio makes 2D magnets extremely sensitive to the surface environment, thus their magnetic properties can be strongly manipulated through proximity with other materials. Recently, the demonstration of epitaxial growth of 2D magnets [3,4] further brings more potential to the material. By directly synthesizing 2D magnet on different substrates, one could manipulate the electrical and magnetic properties of 2D magnet, explore new phenomena at their interface, as well as novel device structures for spintronic applications.

In this talk, we will present the epitaxial growth of 2D magnet MnSe₂ and VSe₂ on various substrate materials and characterize some of them with scanning tunneling microscopy (STM). First, we will present our recent discovery of MnSe₂ [3], one of the first 2D magnets with intrinsic ferromagnetic ordering at room temperature (Fig. 1). The magnetic properties of MnSe₂ grown on GaSe and SnSe₂ are compared. Furthermore, we will also show our exploration of the epitaxial growth of 2D magnet VSe₂ on different substrates, including HOPG, GaAs(111) and Bi₂Se₃. Despite of the large lattice mismatch between VSe₂ and the substrates, all the growths show epitaxial registry, as demonstrated by low energy electron diffraction (LEED) and STM (Fig. 2). The epitaxial alignment and clean interface between VSe₂ and the substrate make it possible to host proximity interaction between them. Finally, some preliminary result of characterizing the 2D magnet materials with spin-polarized STM will be discussed.


5:05pm PCSI-3MoA-38 Investigation of Low-Energy Ion-Implanted Multilayer Epitaxial Graphene, P Micelli, Alessandro Mazza, University of Missouri

There is considerable interest in integrating magnetism with graphene in the hope of creating a new class of spintronic materials. With the recent discovery of a large band-gap semiconducting form of graphene on SiC substrates [1], there are now possibilities for epitaxial graphene-based electronics and integrating magnetism could introduce a new technological dimension. One potential avenue is to make graphene magnetic using defects to generate p-orbital magnetism. Indeed, atomic hydrogen [2] attached to the graphene surface as well as vacancies [3] in graphene have been shown to induce magnetism, while high energy (MeV) proton irradiation can produce ferromagnetism at room-temperature in graphite [4]. However, detailed investigations of these systems are absent so that little is known about the density and configuration of defects, the role of interfaces, or how these relate to magnetism. Moreover, the p-orbital magnetism in these materials is unusual and of scientific interest.

In this talk, we will discuss our investigation [5] of atomic hydrogen implanted at low energies into multilayer epitaxial graphene grown on C-face SiC. The flat interface of this epitaxial system is conducive to x-ray and neutron reflectivity studies where the latter is sensitive to both the H density and magnetism. X-ray diffraction, measured in situ during 500 eV implantation, shows that the spacing between the graphene layers increases significantly with the ion dose. Most of the H ions remain within the sample after dosing as revealed by unpolared neutron reflectivity. It is found from SQUID magnetometry that low-energy H implantation induces a ferromagnetic moment at room temperature. The implications of these results and others, such as ARPES and electron microscopy, will be discussed.


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5:10pm PCSI-3MoA-39 Large Positive Linear Magnetoresistance in the Two-dimensional t₂ₓ Electron Gas at the EuO/SrTiO₃ Interface, Alexander Demkov, The University of Texas

The high mobility two-dimensional t₂ₓ electron gas (2DEG) present at oxide/oxide interfaces is currently under intense investigation [1-2]. In this talk, we will discuss the integration of highly spin-split ferromagnetic semiconductor EuO onto perovskite SrTiO₃ (001). A careful deposition of Eu metal by molecular beam epitaxy results in crystalline EuO growth via oxygen out-diffusion from SrTiO₃ [3]. This in turn leaves behind a highly conductive interfacial layer through generation of oxygen vacancies. Below the Curie temperature of 70 K of EuO, this spin-polarized two-dimensional t₂ₓ electron gas at the EuO/SrTiO₃ interface displays very large positive linear magnetoresistance (MR). Soft x-ray angle-resolved photoemission spectroscopy (SR-ARPES) reveals the t₂ₓ nature of the carriers. First principles calculations strongly suggest that Zeeman splitting, caused by proximity magnetism and oxygen vacancies in SrTiO₃, is responsible for the MR [4]. This system offers an as-yet-unexplored route to pursue proximity-induced effects in the oxide two-dimensional t₂ₓ electron gas [5].


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I will discuss the possibility of significantly enhancing the nonlinear electro-optical response in strained perovskite BaTiO$_3$ and SrTiO$_3$ [5]. For BaTiO$_3$, first principles calculations predict the enhancement for both compressive and tensile strain. The physical origin can be traced to strain-induced phonon softening that results in diverging first order susceptibility. Within the Landau-Ginzburg-Devonshire formalism we demonstrate how, in turn, this divergence results in a diverging second order susceptibility and Pockels coefficient. In epitaxially strained SrTiO$_3$ the electro-optical response is calculated for biaxial strain values ranging from -2.0% to 2.0% relative to the theoretically-optimized lattice constant. Under 1.0% tensile strain, the Pockels tensor components that are zero without strain due to the centrosymmetric structure of SrTiO$_3$ increase dramatically.

Experimentally, we study the nonlinear optical response in a strained thin film ferroelectric oxide BaTiO$_3$ using piezoelectric PMN-PT as a variable strain substrate and La-doped SrTiO$_3$ as a conductive buffer layer [6]. The rotation-anisotropic second harmonic intensity profile shows hysteretic modulation corresponding to strain variation from the inverse piezoelectric response of the substrate. Our results suggest a promising route to enhance the performance of nonlinear optical oxides for the development of future nano-opto-mechanical devices.


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5:50pm PCSI-4MoA-47 Synthesis of Large Area Single-crystalline Freestanding Oxide Membranes, Prastuti Singh, A Swartz, D Lu, S Hong, Stanford University; K Nishio, Geballe Laboratory for Advanced Materials; Y Hikita, Stanford Institute for Materials and Energy Sciences; H Hwang, Stanford University

Recently, a number of 2D materials have been the focus of intense study for the development of nanoelectronics [1]. One potential platform for study is the complex oxide perovskites. Complex oxides are known to exhibit a rich variety of properties such as superconductivity and ferroelectricity due to the local entanglement of the charge, spin and orbital degrees of freedom [2]. In addition, these properties have been shown to be highly tunable by strain, which is an advantage of the 2D geometry compared to bulk samples [3]. The synthesis of complex oxide nanomembranes, while highly challenging due to the 3D nature of the oxygen octahedral bonding, may offer pathways towards highly controllable flexible optical and electronic devices.

In order to take advantage of the unique properties of complex oxides, the final membrane or device must consist of high quality single-crystalline oxide materials. Recently, we have developed a new synthesis technique for crystalline complex oxide membranes and heterostructures compatible with state-of-the-art atomic-scale thin-film growth. The technique makes use of pH-neutral water to selectively etch the sacrificial layer (Sr$_x$Al$_{2}$O$_{3}$) to release the epitaxially grown thin-film from the substrate [4].

In this process, the lattice mismatch between the sacrificial layer and the thin-film plays a critical role in the growth process, membrane release, resulting nanocrystallite size, and material quality. A key question for further developing this highly promising route is to understand the scope of materials and lattice constants which can be accessed via the Sr$_x$Al$_{2}$O$_{3}$ family of materials. Here we take a representative transparent conducting oxide, La-doped BaSnO$_3$, as a model system. The large lattice mismatch of 3.9% with Sr$_x$Al$_{2}$O$_{3}$ leads to high crack density when released due to the large epitaxial strain at the sacrificial layer and thin-film interface. Employing a lattice matched sacrificial layer (Sr,Ba)$_{3}$Al$_{2}$O$_{8}$ (mismatch 0.4%) leads to successful fabrication of millimeter-scale large-area membranes (Fig. 1a) with crystallinity and electronic properties comparable to the epitaxial thin films (Fig. 1b), paving the way for the development of nanomembrane devices.

From these results, we conclude that the ultrafast quenching of spin/valley density at the WSe$_2$/graphene interfaces. In addition, photoluminescence maps show quenched emission enhanced at the same time. Sharp contrast images of MnGe were identified in atomic resolution STM images. These assignments were confirmed by the good agreement between the STM images and DFT-simulated images using the Tersoff-Hamann approximation. Having determined the surface terminations, STM images of the atomic layering order and registry across step edges allows us to uniquely determine the stacking order, and hence chirality of these films, which is difficult with conventional crystallography techniques.

The noncollinear spin state of MnGe stems from 3 interacting spin spirals, the tripod state [1]. We have imaged MnGe by SP-STM whose structure persists across quad-layer atomic steps which necessarily have the same surface termination. In contrast, the observed spiral contrast changes direction across non-quad-layer steps between different surface terminations. Spin-polarized tunneling spectroscopy reveals a pronounced field-dependence on one of these terminations, which is in good agreement with the calculated spin-resolved partial densities of states from DFT. These studies lay the groundwork for 2D-based interfacial heterostructures [1].


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8:00pm PCSI-MoE-4 Ultrafast Spin and Charge Transfer in Monolayer WSe$_2$-Graphene Heterostructure Devices, Michael Newburger, K Luo, Ohio State University-Columbus; K McCreary, Naval Research Laboratory; J Martin, E McCormick, Ohio State University-Columbus; B Jonker, Naval Research Laboratory; R Kawokami, Ohio State University-Columbus

Monolayer transition metal dichalcogenides (TMDs) such as WSe$_2$ have garnered much attention due to their long spin-valley lifetimes and ability to optically excite spin/valley polarization. Additionally, one of the great strengths of TMDs is their ability to compliment other materials, such as graphene, by acting as a means of optical spin injection or proximity coupling. Recently multiple groups have observed efficient, proximity mediated charge transfer in TMD/graphene heterostructures [1]. Moreover, magnetoresistance measurements have demonstrated the ability to optically inject spins from TMD to graphene [2]. However, little work has been done to quantify the speed of spin transfer across a TMD/graphene interface or its effect on spin/valley lifetime. Here we use time-resolved Kerr rotation (TRKR) microscopy to image the spatial dependence of spin/valley dynamics in monolayer WSe$_2$/graphene heterostructures. Under p-type gating, Kerr rotation spatial maps of bare CVD grown WSe$_2$ demonstrate a characteristically spatially dependent, long-lived spin-valley signal [3]. Surprisingly though, these Kerr maps show strong quenching of spin/valley density at the WSe$_2$/graphene interfaces. Time delay scans of the interfaces reveal lifetimes as low as several picoseconds, up to 3 orders of magnitude lower than typical lifetimes in bare WSe$_2$. In addition, photoluminescence maps show quenched emission at the interfaces, whereas photococonductivity is enhanced at the same locations, demonstrating efficient charge transfer from WSe$_2$ to graphene. From these results, we conclude that the ultrafast quenching of spin/valley lifetime is due to transfer of spin information by the efficiently conducted charge carriers.


plane structural changes that should give rise to distinct optical anisotropic responses in monolayers which remains highly unexplored.

We investigate and compare changes in the optical response of 2H-MoTe₂ and 2H-Mo₇₁,W₁₋₃Te₂ alloys as they undergo phase transition between semiconductor-to-semimetal phases in an all vdW device structure using an hBN gate dielectric and graphene contacts. The optical response of the vdW stack are investigated using angle- and polarization-dependent reflection measurements as a function of gate voltage. Initial results showed changes in the optical response of the vdW stack between (1.1–1.4μm) with applied gate voltage in alloys with x=0.09. Furthermore, polarization and temperature-dependent Raman measurements are also performed to map out structural changes in MoO₃/W₂Te₃ as a function of gate voltage. These results will provide new insight into the optical response of these materials to enable new avenues for application in low-voltage and ultrafast modulators and other nanophotonic devices.


Two-dimensional (2D) materials continue to be an exciting area of research due to their interesting properties including large surface-to-volume ratio, high free carrier mobility and ease of stacking with other 2D materials to modular device design. Germanane, a germanium analogue to graphene, has a direct band gap around 1.6 eV that can be tuned by modifying the ligand termination on the Ge scaffold creating opportunity for optoelectronic applications [1]. Germanane, synthesized by deintercalating CaGe₂ with an acid chosen for a desired ligand termination, is sensitive to many factors which impact the behavior of this material. Defects in the Ge scaffold and incomplete reactions can create electronically active states within the band gap [2]. External factors such as ambient pressure and contaminants sitting between 2D layers can also play a large role in the observed electronic properties. We used an atmosphere-controlled photoluminescence spectroscopy (PLS) setup combined with depth-resolved cathodoluminescence spectroscopy (DRCLS) and density functional theory (DFT) calculations to investigate how atmospheric conditions affect germanane. Both pressure and atmospheric composition effects were seen. First, we observed the intensity of the photoluminescence measurement of germanane vanish above a few hundred millitorr. Our original PLS measurements taken in low vacuum agree well with DRCLS collected in ultra-high vacuum (UHV) conditions [2]. If the germanane is in a water-free gas such as N₂, O₂, or Ar atmosphere, the luminescence stays quenched and no further states develop. However, once H₂O is introduced either by simply using ambient air or bubbling a gas through water, a new hydrated state emerges with higher than band gap energy photons emitted at 1.8-1.9 eV which can be removed upon returning the germanane to vacuum. This demonstrates pressure-reversible control of the germanane electronic structure with atmospheric conditions. This work supported by NSF MRSEC under award number DMR-1420451.


The III-V nanowire (NW) technology platform has reached a level of advancement that allows atomic scale tailoring as well as flexible device integration. In particular, controlled axial stacking of Wurtzite (Wz) and Zincblende (Zb) crystal phases is uniquely possible in the NWs[1]. We have previously found that multiphoton electron excitations can be controllably varied across the NW crystal segments [2] and that segments retain their unique electronic properties to the smallest possible scales[3]. In the presented study we employ ultrafast time resolved PEEEM utilizing femtosecond laser sources to explore the initial stages of the photo-carrier relaxation dynamics in InAs nanowires consisting of segments with different crystal structure. To this end, we combine PEEEM with a tunable femtosecond laser source delivering sub 20fs pulses in the visible spectral range and perform spatially resolved one-color pump-probe measurements on individual nanowires. The photoelectron yield is found to increase within approximately 100fs after excitation, followed by an exponential decay with a dominant time constant of about 400fs. We tentatively attribute these signals to the thermalization and the cooling of the photo-excited electrons. Furthermore, we demonstrate local variations of the relaxation times within individual nanowires as a function of excitation light polarization and crystal structure.


8:25pm PCSI-Moe-9 Van der Waals Integration beyond 2D Materials, Xiangfeng Duan, UCLA

The heterogeneous integration of dissimilar materials is a long pursuit of material science community and has defined the material foundation for modern electronics and optoelectronics. The current material integration strategy such as chemical epitaxial growth usually involves strong chemical bonds and is typically limited to materials with strict structure match and processing compatibility. Materials with substantially different lattice structures cannot be epitaxially grown together without generating much too interfacial defects that seriously alter/degrade their intrinsic properties. Alternatively, van der Waals integration, in which pre-formed building blocks are physically assembled together through weak van der Waals interactions, offers a bond-free material integration approach. The flexible “physical assembly” process used in van der Waals integration is not limited to materials that have similar lattice structures or require similar synthetic conditions. It can thus open up vast possibilities for damage-free integration of highly distinct materials beyond the traditional limits posed by lattice matching or process compatibility requirements, as exemplified by the recent blossom in the van der Waals integration of a broad range of 2D heterostructures. Here I will discuss van der Waals integration as a general material integration approach for creating diverse heterostructures with minimum integration-induced damage and interface states, enabling high-performing devices (including high speed transistors, diodes, flexible electronics) difficult to achieve with conventional “chemical integration” approach [1-10]. Recent highlights include the formation of van der Waals metal-semiconductor contacts free of Fermi level pinning to enable the first experimental validation of the Schottky-Mott rule since the initial prediction in 1930s [9]; and the development of van der Waals thin films for high performance large area electronics [10]; and the creation of a new class of van der Waals 2D-molecular superlattices with radically different layers yet atomic precision in each layer [7].


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The nitrogen vacancy (NV) center in diamond is an atomic-scale defect that exhibits remarkably coherent quantum properties in a uniquely accessible way: at room temperature, in ambient conditions, and even immersed in biological environments. NV centers are being explored for a variety of quantum technologies, including quantum sensing and quantum information processing. In this talk, I introduce the physics and materials science behind the success of the NV center and I highlight some of the major achievements of NV-based quantum sensors, the most advanced of NV-based technologies. I present a versatile NV-based imaging platform where we have incorporated an NV center into a scanning probe microscope and used it to image vortices in superconductors [1], skyrmions in thin film magnetic multilayers, and conductivity on the nanoscale [2].

I also outline the challenges facing the widespread use of NV centers in local applications, including spin decoherence [3] and charge state instabilities near interfaces. Using the NV center as a quantum probe of its local environment, we have identified several of the microscopic mechanisms responsible for reduced quantum functionality of near-surface NV centers, thus guiding the ongoing development of quantum control techniques and materials design, pushing towards the ultimate goal of NV-based single nuclear spin imaging.

9:05am PCSI-1TuM-8 Stark Tuning of Single Photon Emitters in Hexagonal Boron Nitride G Nah, D Choi, Ajou University, Korea; J Kim, D Im, Y Kim, POSTECH, Korea; H Seo, Jeun Lee, Ajou University, Korea

Single photon emitters are fundamental resources of quantum optics and quantum information technologies. Recently, the emergence of single photon emission in atomic defects in hexagonal Boron Nitride (h-BN) at room temperature has evoked great interests in 2D-material-based single photon sources. For full exploitation of 2D single photon emitters for quantum technologies, however, the ability to control each atomic defect individually is critical. In this work, we show the electrical control of single photon emission in h-BN induced by an out-of-plane electric field [1]. This has been possible by fabricating a vertical heterostructure of h-BN containing atomic defects with graphene gates. A diverse spectral trail of Stark shifts is measured, providing information on defects’ dipole transitions. The effect also persists at room temperature. We will also show possible ground states of defect structures that can induce the observed Stark shifts.

9:20am PCSI-1TuM-11 Quantum Magnonics in [V(TCNE)], Ezechiel Johnston-Halperin, The Ohio State University

The study of quantum coherent magnonic interactions relies implicitly on the ability to excite and exploit long lived spin wave excitations in a magnetic material. That requirement has led to the nearly universal reliance on yttrium iron garnet (YIG), which for half a century has reigned as the unchallenged leader in high-Q, low loss magnetic resonance, and more recently in the exploration of coherent quantum coupling between magnonic and spin [1] or superconducting [2] degrees of freedom. Surprisingly, the organic-based ferrimagnet vanadium tetracyanoethylene (V(TCNE)) has recently emerged as a compelling alternative to YIG. In contrast to other organic-based materials V(TCNE) exhibits a Curie temperature of over 600 K with robust room temperature hysteresis with sharp switching to full saturation. Further, since V(TCNE) is grown via chemical vapor deposition (CVD) at 50 C it can be conformally deposited as a thin film on a wide variety of substrates with Q rivaling the very best thin film YIG devices [3], which must be grown epitaxially on GGG substrates at 1100 C. While further studies of the CVD V(TCNE) film on a wide range of substrates are needed, the results are consistent with the predictions of existing magnon theory. The results are also consistent with the predictions of the quantum CDM model of Ref. 3. The work is supported by DARPA/MTO Meso program and NSF Grant No. DMR-1507775 and EFRI NewLAW EFMA-1741666.


the tip can be used immediately for surface scanning and hydrogen depassivation lithography. UNCD film-based tips exhibit excellent durability, maintaining consistent scanning performance over very large scan areas. Tip morphology is characterized via STEM and ED.

9:40am PCSI-2TuM-15 Surface Physical and Chemical Processes with an Optical Scanning Tunneling Microscope, Shaowei Li, University of California, Irvine; W Ho, Northwestern University

The desire for observing finer details using optical microscopy particularly in bio-science has pushed technology developments toward the joint spatial-temporal resolution. The combination of optical excitation with scanning probe techniques provides a new window for viewing the unique properties of individual nano-scale objects. The optically excited atoms or molecules can be locally probed by a scanning probe microscope (SPM). The combination of a femtosecond (fs) laser with the scanning tunneling microscope (STM) would enable the study of laser photochemistry to attain simultaneous spatial and temporal resolutions.

Here, we demonstrate the laser photochemistry at single molecule level with a femtosecond laser STM, and ultimately probe the coherence molecular dynamics with joint fs-Å sensitivity. Irradiation of the STM junction with femtosecond laser pulses can generate energetic photo-assisted tunneling electrons. The coupling of laser to the electron tunneling process can shatter the diffraction limited resolution in light induced phenomena and reach the atomic scale resolution of the STM. We show that photo-assisted tunneling electrons can selectively activate individual C-H bonds in an azulene molecule adsorbed on a Ag(110) surface at 8.6 K. Electron energy required to break the bond decreased by 1.5 eV under 820 nm laser illumination, indicating that an electron can be coupled with one photon to induce the reaction. The C-H bond to be activated can be chosen by positioning the tip over the molecule with sub-Å resolution. The inelastic tunneling probe (tipProbe) images taken before and after the reaction provide unambiguous structural identifications of the reaction products.

The coupling of femtosecond laser pulses to the tunneling process enables the investigation of coherence chemistry with joint fs-Å resolution. We observed the coherent vibration driven structural transition of single pyrrolidine molecules adsorbed on a Cu(001) surface with joint fs-Å resolution. The molecular dynamics, including vibrational frequency and lifetime, are determined to drive the coherent structural transition in the molecule. When two molecules are spatially close to each other, the intermolecular interactions lower the vibrational lifetime and downshift the vibration energy. We expect our work with joint fs-Å resolution to open a new avenue into probing single molecule coherent chemistry.

PCSI
Room Ballroom South - Session PCSI-3TuM

2D Materials and Heterostructure Growth
Moderator: Susanne Stemmer, University of California, Santa Barbara

11:00am PCSI-3TuM-31 Chemically and Atomically Ordered States in 2D Crystal Alloys, Nasim Alem, Penn State University

Alloying and doping are considered versatile strategies for tuning charge and heat transport in nanostructures. Whether the resulting alloy structure is random or ordered can have a profound impact on the macroscopic electronic, optoelectronic, vibrational, and transport properties of the material. In this talk, we present structural and chemical ordering1,2 as a mechanism to design anisotropy in the family of 2D transition metal dichalcogenides (TMDs) alloys (Fig. 1). Leveraging recent advancements in atomic resolution scanning/transmission electron microscopy (S/TEM) imaging and spectroscopy, we show the formation of chemically ordered states and vacancy/dopant coupling that leads to unusual relaxation effects around dopant-vacancy complexes leading to local strain and symmetry breaking around individual dopant sites. In addition, we will further uncover the defect structure, i.e. grain boundaries and anti-phase boundaries, and their stability and dynamics in monolayer TMD crystals and their alloys. This understanding can have a strong impact on the synthesis and functionality of novel nanostructure alloys and provides the key to properly design devices for heat dissipation applications, energy storage, electronics, optoelectronics, and thermoelectrics.


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The rapid development of device technologies based on 2D transition metal dichalcogenides (TMDs) causes increasing demand for synthesis of high quality large area monolayer and few layer films. Our previous work demonstrated epitaxial growth of large area monolayer WSe2 films on c-plane sapphire using gas source chemical vapor deposition (CVD). However, the optical and electrical properties of coalesced monolayer films grown on sapphire are negatively impacted by the existence of anti-phase boundaries (APBs) as well as non-uniformities arising from steps and charge-induced doping associated with the sapphire surface. Prior studies demonstrated a preferred domain orientation for TMDs grown on hBN and first-principle calculations suggest this phenomenon originates from single atom vacancies on the hBN surface that act as nucleation sites. In this study, we further investigate the mechanism of defect-assisted domain alignment of 2D TMDs on hBN and demonstrate the growth of fully-coalesced WSe2 films on hBN with a reduced density of APBs and improved optical and electrical properties compared to films grown on sapphire.

WSe2 monolayer films were grown by gas source CVD at 800°C using W(CO)6 and H2Se in a H2 carrier gas employing a multi-step process to separately control nucleation density and lateral growth and coalescence of domains. Single crystal hBN flakes exfoliated from bulk crystals and transferred onto c-plane sapphire were used as substrates. Plasma treatment and NH3 annealing were used to modify the surface defect density of hBN. Detailed studies of WSe2 deposition on hBN as a function of growth conditions and substrate pre-treatment confirm that domain nucleation is controlled by the surface defect density rather than the precursor concentration. Over 90% of WSe2 domains have consistent orientation via the defect-assisted growth. Through careful control of nucleation and extended lateral growth time, fully coalesced WSe2 monolayer films on hBN were produced for subsequent characterization. High resolution scanning transmission electron microscopy (S/TEM) analysis demonstrates the absence of APBs in coalesced regions formed by the merging of 0° oriented domains. Temperature-dependent photoluminescence measurements show sharp and enhanced exciton and trion emission peaks, with no defect-related bound exciton emission from monolayer WSe2/hBN down to 7 K. Additionally, FESEM images of WSe2/hBN films transferred to SiO2/Si substrates show an order of magnitude increase in room temperature carrier mobility (~5 cm2/V-s) compared to similar devices fabricated using monolayer WSe2 films transferred from sapphire.

11:35am PCSI-3TuM-38 Novel Sulfide Heterostructures from Designed Precursors, D Roberts, University of Colorado at Boulder; Sage Bauers, J Perkins, National Renewable Energy Laboratory; C Stoldt, University of Colorado at Boulder; A Zakutayev, National Renewable Energy Laboratory

Composite 2D material systems present not only unique structural and electrical phenomena but can be intentionally designed to elicit properties desirable for a specific application. Existing reports of chalcogenide heterostructures have shown the ways in which varying precursors on the structure and quality of our crystalline end product. Challenges inherent in sulfur-based depositions are also addressed.

In this work we demonstrate the synthesis of multilayer sulfide heterostructures crystallized from amorphous precursors via sputter deposition. We utilize a combinatorial approach to depositions in order to reduce time and specificity needed in calibrating the time needed to deposit constituent components of such structures. A schematic of this setup can be seen in Fig. 1. Here we will focus on spatially resolved structural characterization of these combinatorial samples with respect to changes in long range ordering indicative of improved crystallinity. Additionally, we investigate the role of off-stoichiometry in as-deposited precursors on the structure and quality of our crystalline end product. Challenges inherent in sulfur-based depositions are also addressed.

Tuesday Morning, January 15, 2019
8:30 AM
Tuesday Morning, January 15, 2019

11:40am PCSI-3TuM-39 Rotational Alignment of Epitaxially-grown hBN on Macrostepped Graphene/SiC(0001) Single-Crystal Substrates, Daniel Pennachio, University of California, Santa Barbara; C Ornelas-Skarin, University of California, Irvine; N Wilson, E Young, A McFadden, T Brown-Heft, University of California, Santa Barbara; K Daniels, R Myers-Ward, K Gaskill, C Eddy, Jr., U.S. Naval Research Laboratory; C Palmstrom, University of California, Santa Barbara

Many of the intriguing properties of 2D devices rely on the relative rotational alignment between layers. For instance in the graphene/hBN system, band structure modulation can occur at specific alignments [1], but a misalignment may be beneficial if innate graphene properties are to be examined. To allow for scalable graphene/hBN heterostructure formation, this work investigates hBN growth on single-crystal epitaxial graphene (EG) on macrostepped SiC(0001) substrates. The presented results suggest these macrosteps may influence the hBN epitaxial relation such that a metastable, 30° in-plane hBN/EG alignment is more favorable with certain growth conditions than the direct 0° alignment between hBN/graphene, despite their similar crystal structures.

Plasma-enhanced chemical beam epitaxy (PE-CBE), an ultra-high vacuum (UHV) compatible process, was utilized to provide a clean environment for examination of the hBN structural, electrical, and chemical properties via in-situ and in-vacuo characterization methods. To determine the effect of substrate macrostep morphology, EG on SiC (0001) substrates with no offcut and with a 4° offcut toward <11-20>SiC were tested. The alignment of the hBN/EG/SiC(0001) heterostructure was studied by relating in situ electron diffraction to nuclei edge directions. In addition, cross-sectional transmission electron microscopy (TEM) confirmed registry of the hBN to the EG/SiC substrate, while plan-view TEM showed in-plane alignment and uniformity. The macrostep-directed epitaxy of hBN on EG highlighted in this work highlights the possibility of various rotational alignment during van der Waals epitaxy, a promising feature for direct growth of 2D heterostructures.

PCSI
Room Ballroom South - Session PCSI-TuE

Quantum Materials?

Moderator: Debdeep Jena, Cornell University

7:00pm PCSI-TuE-1 Magnetic Weyl Semimetals, Claudia Felser, J Goeth, K Manna, E Lui, Y Sun, Max Planck Institute, Germany  INVITED

Topology a mathematical concept became recently a hot topic in condensed matter physics and materials science. One important criteria for the identification of the topological material is in the language of chemistry the inert pair effect of the s-electrons in heavy elements and the symmetry of the crystal structure [1]. Beside of Weyl and Dirac new fermions can be identified compounds via linear and quadratic 3-, 6- and 8-band crossings stabilized by space group symmetries [2]. Binary phosphides are the ideal material class for a systematic study of Dirac and Weyl physics. Weyl points, a new class of topological phases was also predicted in NbP, NbAs, TaP, MoP and WP2. [3-7]. In magnetic materials the Berry curvature and the classical AHE helps to identify interesting candidates. Magnetic Heusler compounds were already identified as Weyl semimetals such as Co$_2$YZ [8-10], in Mn$_3$Sn [11,12] and Co$_3$SnS$_2$ [13].

The Anomalous Hall angle helps to identify even materials in which a QAHE should be possible in thin films. Besides this k-space Berry curvature, Heusler compounds with non-collinear magnetic structures also possess real-space topological states in the form of magnetic antiskyrmions, which have not yet been observed in other materials [14].


7:30pm PCSI-TuE-7 Status of Purity for Bulk Samples and Implications for Quantum States, Arthur Ramirez, University of California Santa Cruz  INVITED

Present interest in topological materials, some with quantum entangled ground states, is driven in part by a proliferation of new bulk compounds. These materials include structures that lack inversion or time-reversal symmetry, leading to Weyl semimetal (WSM) behavior, and triangular or honeycomb systems capable of supporting a quantum spin liquid (QSL) states. The realization of either undoped WSM or fully entangled QSL phases will likely require levels of crystallinity far beyond that realized in present samples. I will sketch out a few examples in both classes of systems and discuss approaches to achieve high purity bulk material.

8:00pm PCSI-TuE-13 Rump Session,
9:05am PCSI-1WeM-8 Electronic Charge Transport in Solution-processed Vertically Stacked 2D Perovskite Quantum Wells, H Tsai, Rice University; R Asadpour, Purdue University; M Kanatzidis, Northwestern University; M Alam, Purdue University; A Mohite, Rice University; Wonyi Nie, Los Alamos National Laboratory

State-of-the-art quantum well based devices such as photovoltaics, photodetectors and light emission devices were enabled by understanding the nature and the exact mechanism of electronic charge transport. Ruddlesden-Popper halide perovskites are two-dimensional solution-processed quantum wells and have recently emerged as highly efficient semiconductor for solar cell approaching 13% in power conversion efficiency. However, further improvements will require an understanding of charge transport mechanisms, which are currently unknown and further complicated by the presence of strongly bound excitons. In our study, we discovered that the carrier transport is closely related to the structure and stacking of those quantum wells. Combining systematic device characterization and simulation, we conclude that the photo generated electron-hole pairs need to overcome the multiple internal potential barriers for collection to occur. The potential barriers that block the efficient separation of electron-hole pairs are attributed to the misalignment between crystalline slabs. Both of those properties are unfavorable for photovoltaic cell operation. Here we elucidate the critical role of field-assisted charge carrier separation that overcomes these bottlenecks leading to the efficient photocurrent collection. On the other hand, the structure of the 2D perovskites could promote the radiative recombination by spatially localizing the electrical injected carrier, which makes them an excellent material for light emitting diodes.

9:10am PCSI-1WeM-9 N-type Doping in Organic Semiconductor Thin Films by using a Dendritic Oligoarylamine-substituted Benzimidazole Dopant, Yuji Yoshishashi, Keio University, Japan

Organic n-type doping with donor dopants has not been established well because of air instability of conventional donor dopants. With this background, we have focused on imidazole-based compounds as solution-processable and pure organic n-type dopants. These compounds are known as strong single-electron reductants. However, these dopants are quickly oxidized in solution phase in ambient condition. In this work, we report an approach for increasing the stability of benzimidazole dopant molecule in solution phase by attachment dendritic oligoarylamine (N,N-bis-[4-di-(4-anilino-amino) phenyl]amine) at the 2-position of the imidazole ring (N3-DMBI-H shown in Fig. 1) [1].

N3-DMBI-H was newly synthesized by ourselves. N3-DMBI-H solution in chlorobenzene (CB) revealed much better stability in ambient air than solutions of other benzimidazole dopants. [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) solution (in CB) was dropcast onto Si substrates covered with 200 nm-thick SiO2 layer. Doping concentrations of N3-DMBI-H were 0, 0.5, 2 and 5 wt%. After that, the dropcast films were dried and heated at 100°C overnight to activate the dopants. The above processes were performed in N2-filled glovebox. After Au electrodes (thickness: 25 nm) were deposited onto the PCBM film surfaces by vacuum evaporation, we measured two-terminal current-voltage (I-V) characteristics of PCBM films under a vacuum condition (10-8 Pa).

Figure 2 shows two-terminal I-V characteristics of undoped and N3-DMBI-H doped PCBM films. The gap distance between the two contact electrodes was 50 μm. As shown in Fig. 2, doping N3-DMBI-H into PCBM increased the current value by more than five orders of magnitude. The electrical conductivity of the N3-DMBI-H-doped PCBM thin film was reported to be 6.39 × 10^-4 cm^2/Vs, which is 10^5 times larger than the undoped PCBM: 6.62 × 10^-5 cm^2/Vs. This result suggests that the electric resistance of PCBM thin films considerably decreased by N3-DMBI-H doping, due to carrier (electron) doping effects.

1WeM-9


9:15am PCSI-1WeM-10 Multi-scale Modeling of Molecule-Surface Interactions for Improved Charge Transfer across Photoelectrochemical Interfaces, A Iyer, K Kearney, University of Illinois at Urbana-Champaign; A Rockett, Colorado School of Mines; Elif Ertekin, University of Illinois at Urbana-Champaign INVITED

The design of efficient, stable photoelectrochemical devices requires the use of complex heterojunctions composed of semiconducting, protective, and catalytic layers. Understanding the nature of charge transport across these interfaces is challenging, due to the complexity of the interfaces and possibility of competing charge transfer mechanisms. W e present our recently developed multiscale approach that combines first-principles density functional theory (DFT) and solid-state drift/diffusion device scale modeling to give insights into the nature of charge transport across photoelectrode interfaces [1-3]. Fig. 1. DFT is used to estimate the surface dipole induced by the functionalization, and the device software waAMPS is used to predict experimentally measurable features such as the JV curve and the open-circuit voltage. Using this approach, we are able to identify the mechanism of hole transfer across n-Si(111)-rTiO2 interface and occurs by two processes—thermionic emission and/or intraband tunneling—where the interpaly between them is regulated by the interfacial molecular dopant. Finally we will highlight how molecule/surface interactions can be used to model doped silicon slabs at experimental doping densities in a computationally tractable manner.

9:45am PCSI-1WeM-16 Scanning Electrochemical Microscopy of Graphene-based Hybrids: Insights into Physicochemical Interfacial Processes and Electroweactive Site Density Distribution, Sanju Gupta, Western Kentucky University

Surface (and interfacial) science is found in various environments of scientific significance including biomembranes, ocean and atmospheric chemistry, applied electrochemistry and at the grand challenges of energy-water nexus [1]. Molecular redox behavior on the surface and at the interface is drastically different than bulk counterparts.

Wednesday Morning, January 16, 2019

PCSI
Room Ballroom South - Session PCSI-1WeM

Hybrid and Mixed-Dimensional Interfaces

Moderator: A. Alec Talin, Sandia National Laboratories

8:30am PCSI-1WeM-1 Nanoimaging and Spectroscopy of Emerging Photovoltaic, Marina Leite, University of Maryland INVITED

Solar energy can deliver the >184 000 TWh per annum required to meet the current worldwide energy needs. Yet, High-performance and low-cost photovoltaics (PV) are still required to successfully substitute fossil fuel-based technologies. Hybrid perovskites and thin-film polycrystalline materials are promising options for high-performance and low-cost PV. These materials present mesoscale constructs, with nano- and microscale grain and boundaries that individually contribute to the devices’ optoelectronic behavior [1,2]. For hybrid perovskites, their stability is the primary limiting factor towards commercialization. Thus, we resolve the dynamic optical [3] and electrical [4] responses from the macro- to the nanoscale, as these materials are exposed to: water, oxygen, temperature, bias, and illumination. We further propose a machine learning (ML) tactic to deconvolute the individual and combined effects of each parameter on device stability. We elucidate ion motion within the perovskite grains by a fast scanning probe microscopic new method that enables us to spatially (<20 nm) and temporally (msec) resolve the devices’ open-circuit voltage (Voc) [Fig 1] [4,5]. In the realm of polycrystalline materials, we demonstrate a novel AFM-based approach to image local Voc variations, based on illuminated Kelvin-probe force microscopy [6]. Our functional imaging paradigm provides a new platform to map device performance with nanoscale spatial resolution.


In this talk, we demonstrate scanning electrochemical microscopy (SECM) is a powerful tool to investigate dynamic physical-chemical processes at surfaces and buried interfaces. This technique helps to determine ion (or electron) transfer kinetic rate, diffusion coefficient, imaging electrochemical redox reactions and activity. The significant advantage offered by SECM is its capability of probing chemical information at the solid/liquid interfaces. A constant potential is applied to the tip and electrochemical working electrode (i.e. the substrate in electrolyte) to drive reaction of redox species (or mediator) in bulk electrolyte solution to probe the surfaces of graphene-based hybrids, relevant for electrochemical energy systems. The micro-configured cyclic voltammograms, probe approach (current versus tip–substrate distance) curves in feedback and imaging modes, for graphene/CNT, graphene/transition metal oxide and aerogels are chosen as case examples to probe ion adsorption, charge transfer dynamics and to map highly electroactive (‘hot spots’) edge sites. The SECM setup has a resolution of ~40 nm and can locate and relocate areas of interest precisely after a coarse image. The heterogeneous electrode surfaces comprised of graphene nanosheets (conducting)/other nanomaterials (semiconducting) exhibit peak and valley tip current behavior and site distribution and the data is analyzed in terms of reactive basal plane and edge plane sites distribution, and help to determine heterogeneous rate constant using modeling and fitting experimental data. The findings reinforce the available electron density states in the vicinity of the Fermi level contributing to higher electroactivity, faster interfacial diffusion, and shorter distances for electron transfer, facilitated through molecular and chemical bridges [1].


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Thursday Morning, January 17, 2019

Session PCSI-2WeM: Exploiting Ions in Devices

11:00am PCSI-2WeM-31 Epitaxial Nitride Semiconductor/Superconductor Heterostructures, Debdeep Jena, Cornell University

A new development in MBE growth of lattice-matched NbN/AlN/GaN heterostructures has allowed the integration of GaN based high-electron mobility transistors (HEMTs) with MBE grown NbN superconductors. Structural and electronic properties of these heterostructures and the effect of interfaces will be discussed. Attempts to obtain the quantum Hall effect in the 2DEGs epitaxially grown on the superconductor will be discussed. Finally, progress towards the MBE growth of NbN/AlN/NbN Josephson junctions will be reported.

11:30am PCSI-2WeM-37 Wafer Bonding Approach for Epitaxial Al/GaAs(001)/Al Tri-layers, Anthony McFadden, M. Seas, University of California, Santa Barbara; C McRae, R Lake, National Institute of Standards and Technology; J Wen, J Wang, I Arslan, Argonne National Laboratory; D Pappos, National Institute of Standards and Technology; C Palmstrøm, University of California, Santa Barbara

Superconductor-insulator-superconductor (Josephson) junctions utilizing amorphous oxide barriers have been studied extensively, however relatively little work has been done using single crystal semiconductors in place of amorphous oxide barriers. This is likely due to difficulty in fabrication of such structures including symmetry mismatch of the semiconductor to the superconductor and the reactions and roughening that may occur at the temperatures needed for semiconductor growth. This work focuses on a wafer bonding approach, subsequent substrate removal, and superconductor regrowth for fabrication of Al/GaAs(001)/Al Josephson junctions. AlGaAs/GaAs/Al structures are grown by molecular beam epitaxy on GaAs(001) substrates and wafer-bonded to Si. The substrate and sacrificial AlGaAs layers were removed by selective wet etching followed by surface cleaning in ultrahigh vacuum and aluminum regrowth. The wafer bond and Al/GaAs interfaces are studied by transmission electron microscopy (TEM). X-ray photoelectron microscopy (XPS) is used to determine GaAs surface cleaning conditions compatible with the wafer bonding process following substrate removal. X-ray diffraction (XRD) and reflection high energy electron diffraction (RHEED) is used to assess crystalline quality and orientation of the epitaxial aluminum.
can switch significantly below 1V; developing non-volatile memory operating near the thermal voltage limit is a grand challenge.

In this work, we use two silicon-free electrochemical devices to build non-volatile memory that operates below 300 mV (Fig. 1a). The first device is an ion insertion transistor which electrochemically shuttles lithium ions and electrons between the gate and the channel, analogous to a battery. Because the ions are mobile and move with the electrons, the process is charge neutral, and up to $10^{21}$ cm$^{-3}$ of electrons and ions can be reversibly shuttled between the gate and channel without electrostatic charging. The second device is a diffusive memristor operating based on Ag$^+$ migration and filament formation in the ON state, and diffusive filament dissolution to the OFF state. The low activation energy for Ag$^+$ motion enables the device to switch with low applied voltages. The combination of high charge density of the ion insertion transistor and low leakage current of the diffusive memristor enables these two electrochemical devices to retain memory. Because both devices operate at low voltage, we can linearly tune the electronic conductance using sub-300-mV voltage pulses (Fig. 1b). This device is also compatible with a V/2 crossbar select scheme without a select transistor, and demonstrates that non-volatile synaptic memory near the thermal voltage limit is attainable for low-power electronics.


Lately, scanning ion conductance microscopy (SICM), has emerged as a versatile non-contact imaging tool. To obtain spatially-resolved electrochemical information, scanning electrochemical microscopy (SECM), also known as the chemical microscope, has been developed [1]. Hybrid SICM-SECM techniques have been developed, in which the SICM compartment provides the accurate probe-sample distance control, while the SECM compartment measures the faradaic current for electrochemical information collection [2].

In this work, we demonstrate the use of an Atomic Force Microscopy (Park NX10) in combination with an ammeter for concurrent topography imaging and electrochemical mapping. The SICM-SECM probe consisted of a Au crescent electrode (AuE) on the peripheral of a nanopipette. High resolution probe-substrate distance control was obtained by the ion current feedback from SICM, while simultaneous electrochemical signal collection was achieved via the AuE from SECM. As a proof-of-concept experiment, a Au/Pyrex pattern standard sample was imaged with the SICM-SECM technique. The Au bar and the Pyrex substrate were clearly resolved from the SICM topography image, with the bar height and pitch width closely matching the actual values. In terms of the electrochemical property mapping, higher Faradaic current was seen when the probe was scanned over Au bar as a result of redox cycling, while lower Faradaic current was observed when the probe was over Pyrex substrate due to hindered diffusion. The capability of the SICM-SECM technique described here holds promise of many exciting applications in the field of electrochemistry, material science and battery research.

Thermal atomic layer etching (ALE) is based on sequential, self-limiting surface reactions. Thermal ALE is the reverse of atomic layer deposition (ALD). Thermal ALE has been demonstrated for many materials including Al₂O₃, HTO₂, ZrO₂, TiN and W. This talk will focus on thermal Si ALE using oxidation and “conversion-etch” mechanism. During this process, the Si surface is oxidized to a silicon oxide layer using O₂ or ozone. The silicon oxide layer is then converted to an Al₂O₃ layer using trimethylaluminum (TMA) [1]. Subsequently, the Al₂O₃ layer is fluorinated [1] by HF to an AlF₃ layer prior to the removal of the AlF₃ layer by a ligand-exchange reaction using TMA [1]. This reaction sequence is shown in Figure 1.

Si ALE was studied using silicon-on-insulator (SOI) wafers in a warm wall reactor with a hot sample stage. In situ spectroscopic ellipsometry (SE) was employed to monitor the thickness of both the silicon and the silicon oxide layer during Si ALE. These studies observed that the silicon film thickness decreased linearly with number of reaction cycles while the silicon oxide thickness remained constant. Using an O₂-HF-TMA reaction sequence, the Si ALE etch rate was 0.4 Å/cycle at 290°C as shown in Figure 2. Comparable etching rates were observed using ozone instead of O₂ as the oxidant.

Thermal Si ALE should be useful in advanced semiconductor fabrication. Thermal Si ALE could also be utilized for atomic-scale polishing and cleaning of silicon surfaces. In addition, there may be applications in other areas such as silicon-based optoelectronics, photonics and MEMS fabrication.

In this study, fundamental properties of graphene-assisted chemical etching, which is the preferential etching method for a Ge surface in contact with single sheets of reduced graphene oxide (rGO) in O₂-containing water were described. An rGO solution was prepared by chemical reduction of a GO solution and spin-coated on a Ge(100) surface. The sample was immersed in O₂-containing water for 24 h. We show the change in surface morphology of rGO sheet-loaded Ge upon immersion in O₂-containing water. The sheet thickness ranged from 0.8 to 1.2 nm and single rGO sheets were well dispersed after our sample preparation. Then the Ge surface was preferentially etched under the rGO sheets in O₂-containing water. This enhanced etching did not occur using water without dissolved O₂ molecules, indicating that rGO-assisted chemical etching is mediated by an oxidant (O₂ molecules) in a solution (water) [1]. Next, the dependence of etching rate on water temperatures was investigated. The etching rate considerably depended on water temperatures (e.g., 1.9 nm/h at 22 °C and 15.1 nm/h at 48 °C). The Arrhenius plot from this data permitted the estimation of activation energy for this etching mode.

We used laser irradiation to provide external energy for the thermal annealing at the local area of GO thin film (selective reduction). From other side this method is cheap, eco-friendly and easy to perform. Using this method, anyone can make electrical circuits of different shapes at the flexible transparent substrates with carbon nanowires, made beyond the diffraction limit without special equipment and conditions. To pattern rGO conductive lines we used different substrates and different lasers: CO₂ laser with λ=1064 nm and portable laser engraver with λ=405 nm. Figure 1 demonstrated rGO patterning by the laser irradiation.

The key result of this contribution came out after applying the highest laser power. Even though the patterned material was completely ablated in some regions, we still observed a significant electrical conductivity along the pattern (Figure 2). This observation implies that by optimizing the laser parameters, and under higher power than has been reported previously, it is possible to achieve confined rGO regions: the edges of the patterns. Conductive rGO patterns can thus be achieved with spatial dimensions much smaller than the laser spot size.

4. Gil Gonzalez et al., Carbon, 129 (2018) 63 - 75
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2:30pm PCS1-1WeA-7 Fundamental Properties for Enhanced Etching of Ge Surfaces in Water Assisted by Single Sheets of Reduced Graphene Oxide, Tomoki Hirano, Y Nakata, H Yamashita, S Li, K Kawai, K Yamamura, K Arima, Osaka University, Japan

Metal-assisted chemical etching is an emerging technology for fabricating various three-dimensional nanostructures on a semiconductor surface for future electronic and optical devices. Thus far, our group has reported that a Ge surface in contact with noble metals, including Pt and Ag, is selectively etched in O₂-containing water. However, it is extremely difficult to remove residual metallic particles on the processed Ge surfaces. To resolve this issue, graphene is used, which supposedly functions as a catalyst free from metals.

In this study, fundamental properties of graphene-assisted chemical etching, which is the preferential etching method for a Ge surface in contact with single sheets of reduced graphene oxide (rGO) in O₂-containing water were described. An rGO solution was prepared by chemical reduction of a GO solution and spin-coated on a Ge(100) surface. The sample was immersed in O₂-containing water for 24 h. We show the change in surface morphology of rGO sheet-loaded Ge upon immersion in O₂-containing water. The sheet thickness ranged from 0.8 to 1.2 nm and single rGO sheets were well dispersed after our sample preparation. Then the Ge surface was preferentially etched under the rGO sheets in O₂-containing water. This enhanced etching did not occur using water without dissolved O₂ molecules, indicating that rGO-assisted chemical etching is mediated by an oxidant (O₂ molecules) in a solution (water). Next, the dependence of etching rate on water temperatures was investigated. The etching rate considerably depended on water temperatures (e.g., 1.9 nm/h at 22 °C and 15.1 nm/h at 48 °C). The Arrhenius plot from this data permitted the estimation of activation energy for this etching mode.

2:35pm PCS1-1WeA-8 Laser-patterning of Graphene Oxide Beyond the Diffraction Limit, Maksim Fatkullin, Tomsk Polytechnic University, Russia

Graphene oxide (GO), same as graphene itself, attracted a tremendous attention since its re-discovery in 2004 [1]. Main advantages of GO are: water dispersible, flexible and the greatest one its tunable conductivity. Conductivity changing due to reduction process, during which dielectric GO becomes to conductive reduced graphene oxide (rGO). Reduction could be done in different ways, but all of them are either chemical or thermal [2].

The most part of reduction methods are ex-pensive and not scalable, for example reduction using atomic force microscopy (AFM) tip or electron beam [3][4]. The other limitation of these methods is that they attracted all volume of material.

We used laser irradiation to provide external energy for the thermal annealing at the local area of GO thin film (selective reduction). From other side this method is cheap, eco-friendly and easy to perform.

Using this method, anyone can make electrical circuits of different shapes at the flexible transparent substrates with carbon nanowires, made beyond the diffraction limit without special equipment and conditions. To pattern rGO conductive lines we used different substrates and different lasers: CO₂ laser with λ=1064 nm and portable laser engraver with λ=405 nm. Figure 1 demonstrated rGO patterning by the laser irradiation.

The key result of this contribution came out after applying the highest laser power. Even though the patterned material was completely ablated in some regions, we still observed a significant electrical conductivity along the pattern (Figure 2). This observation implies that by optimizing the laser parameters, and under higher power than has been reported previously, it is possible to achieve confined rGO regions: the edges of the patterns. Conductive rGO patterns can thus be achieved with spatial dimensions much smaller than the laser spot size.

4. Gil Gonzalez et al., Carbon, 129 (2018) 63 - 75
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2:40pm PCS1-1WeA-9 Maskless Si Nano-wall Formation by Wet-etching Process using a Femtosecond Laser Irradiation, S Lee, Pusan National University, South Korea; Hyun Hwi Lee, Pohang Accelerator Laboratory, South Korea; H Kim, Pusan National University, South Korea

Recently, ultrashort pulsed laser direct writing technique has been intensively investigated to develop a nanoscale fabrication enabling high aspect ratio. In the referred applications, laser induced nanostructures are formed with well manipulated laser beams in small area. On the other hand, Laser Induced Periodic Surface Structure (LIPSS) has attracted increasing attention for the possibility to generate periodic nanoscale structures in large area with relatively simple optical configurations. LIPSS is a self-organized one-dimensional periodic structure which is formed when multiple laser pulses with the laser fluence near ablation threshold are exposed. These self-induced nanostructures are often categorized into Long Spatial Frequency LIPSS (LSFL) and High Spatial Frequency LIPSS (HSFL) by their periodicity. The periodicity of LIPSS is varied by the wavelength of the laser and the material properties of the substrates. The orientation of the LIPSS is affected by the laser polarization. In case of the LSFL, the orientation is observed almost perpendicular with respect to the incident laser polarization. Therefore, LIPSS with direct-write scheme has been applied in rapid production of functional surfaces on large area such as superhydrophobic surfaces, enhanced absorption, cell adhesion, and tribological applications.

However, these demonstrations utilized the LIPSS property to increase the surface area by desirable surface roughening or enhancing surface properties. Relatively less attention was paid to the morphological changes of LIPSS followed by a chemical etching.

This presentation will introduce a new mask-free patterning technique of Si, which is combined with a conventional wet-etching process and direct-write LIPSS patterns of Si. The technique is a two-step process. First, a femtosecond laser irradiates a Si surface to generate one-dimensional LIPSS silicon on the surface. Conventional wet-etching solvents, such as KOH and TMAl (trimethylaluminum hydroxide), etch the LIPSS to form a periodic micro-cell surrounded by nanowalls with the height of a few hundred nanometers. The distance between the nanowalls was approximately one micrometer and the bottom surface of the cell was atomically flat which is sufficient to grow organic semiconducting thin films for organic devices. The bottoms of micro-cells surrounded by the nanowalls were considerably flat with a 3.10 nm surface roughness. A pentacene layer was deposited on the micro-cells of a Si surface to evaluate the film properties by grazing incidence wide angle x-ray scattering measurements.
The interface of a conventional BCS superconductor (SC) and a topological insulator (TI) is predicted to host an exotic state of matter known as a topological superconductor, the elemental excitations of which could potentially enable quantum computing schemes that are robust against error produced by decoherence. The direct synthesis of a SC-TI heterostructure, however, is challenged due to structural dissimilarities and high interface reactivities between common superconductors and topological insulators. Here, we report on the synthesis and properties of wafer-scale (Bi,Sb)2Te3/graphene/2D-Ga heterostructures grown in part via a new method, i.e. confinement heteroepitaxy (Chet), pioneered by the Robinson group [1]. Chet enables us to intercalate and form atomically thin gallium (Ga) layers at the interface of 2L epitaxial graphene (Gr) and its native SiC (0001) substrate. The graphene-encapsulated 2D-Ga films are predominantly 2-3L thick, crystalline, and, epitaxially registered to the SiC, as confirmed by high-resolution scanning transmission electron microscopy (HR-STEM) (Fig. 1a). The Gr/Ga films exhibit a superconducting state with zero resistance at a transition temperature of $T_c \sim 4 \, \text{K}$ (Fig. 1c), which is higher than that of bulk a-Ga ($T_c \sim 1.08 \, \text{K}$). In addition to serving as a capping layer for the 2D-Ga film, the Gr layer is both a reaction barrier and an ideal substrate for the subsequent molecular beam epitaxial (MBE) growth of a Ti material (Bi,Sb)2Te3. HR-STEM and energy-dispersive X-ray spectroscopy (EDS) mapping shown in Fig. 1b demonstrates the atomically sharp interfaces and high-quality layer-by-layer growth of all constituent layers in a heterostructure of 6 quintuple-layer (Bi,Sb)2Te3 grown on Gr/Ga. Reflection high energy electron diffraction pattern and angle-resolved photoelectron spectroscopy measurements verify its crystalline integrity and the Dirac surface bands of the Ti film. First-principles calculations reveal the electronic band structure of the heterostructure, which is conducive to proximity-induced superconductivity in the Ti film. Our approach circumvents several key challenges in making high-quality SC-TI heterostructures to offer a new route towards the realization of topological superconductivity.


3:00pm PCSI-1WeA-13 Tracking Defects through Ultra-Thin Layered Complex Oxides, B.A. Noeges, The Ohio State University; J. Lee, C Eom, University of Wisconsin-Madison; L Brillson, The Ohio State University
Improving ultra-thin films and devices requires characterization techniques capable of resolving defects at near-nanoscale depths. Defect formation in and nearby ultra-thin layers can produce effects that permeate the layer and alter interface properties. Resolving defects on this scale is especially important for complex oxide heterostructures like LaAlO$_3$/SrTiO$_3$ where just nanometers thick layers of LAO and STO produce a highly conductive interface between the insulating materials. Interfacial majority carriers are controlled through choice of neighboring atomic planes at the interface. These interfaces are referred to as two-dimensional electron or hole gases (2DEG/2DHG) depending on carrier type since conduction is confined in-plane. The performance of the 2DEG is strongly influenced by nearby defects, like oxygen vacancies which are donors and increase carrier concentration while reducing mobility. The 2DHG interface is even more strongly affected and can’t form unless nearby oxygen vacancies are sufficiently suppressed [1]. We used depth-resolved cathodoluminescence spectroscopy (DRLCS) alongside advanced growth techniques designed to carefully control defect formation to systematically study the interplay between native point defects, defect complexes and interface carrier conductivity. DRLCS is an ideal technique to investigate defects in ultra-thin layers since probe depth is tunable on the near-nanoscale by adjusting voltage of an incident electron beam. With this control, cathodoluminescence can be obtained from nanometers below the film surface through interfaces and hundreds of nanometers into the substrate, providing information about the defects present in each layer. DRLCS guided by DFT calculations can identify oxygen vacancy ($V_0$) defects as well as assorted metal cation related defects like Sr vacancies and Ti on Sr antisite ($T_{\text{Sr}}$) defects [2]. Certain defects can suppress others, i.e., $T_{\text{Sr}}$ formation suppressing oxygen vacancy defects creating extremely clean, high mobility 2DEG interfaces. DRLCS is a unique tool for tracking defect concentration through ultrathin oxide layers to determine the role of defects in space charge regions. Growth control combined with near-nm DRLCS distribution measurements inside complex oxide heterostructures provides a powerful approach to achieve advanced electronic features and improved device quality. Support by NSF DMR-18-00310.


that the stochastic valley noise is measurable by optical means and encodes the true intrinsic timescales of valley relaxation, free from any pumping or excitation [3].

Using this new fluctuation-based methodology we measure very long valley relaxation dynamics of both electrons and holes in a single electrostatically-gated monolayer of WSe₂. Valley noise frequency spectra reveal long intrinsic valley relaxation with a single sub-microsecond time scale. Moreover, they validate both the relaxation times and the spectral dependence of conventional pump-probe measurements, thereby resolving concerns about the role of dark excitons and trions in studies of long-lived valley relaxation.


5:00pm PCSI-2WeA-37 The Electronic Structure of 2D Materials, Justin Wells, Norwegian University of Science and Technology, Norway

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The electronic bandstructure contains complete information about the occupied electronic states which exist in a material. i.e. intrinsically it includes information on doping, Fermi velocities, confinement, the orbital nature of the bands, spin-coupling and all possible interactions. Measuring the electronic bandstructure is possible using techniques derived from photoelectron emission spectroscopy; and due to the exceptionally short probing length, this works particularly well for 2D materials and surface phenomena.

In this talk, I will describe some recent examples from our own research. In particular, I will describe how certain materials allow a smooth 3D to 2D transition, such that the role of dimensionality can be disentangled. Specifically, I will discuss the unusual phonon mediated scattering/coupling in graphene/graphite [1-3], the spin texture of monolayer transition metal dichalcogenides (TMDCs), and how the origins of this are derived from local symmetry breaking in the parent bulk compounds [4,5]. Finally, I will discuss the 3D to 2D transition in group-IV semiconductors (silicon and diamond) created as a result of a high-density dopant plane within the bulk material (see figure), and the implications of this confinement for the ultimate miniaturisation of classical and quantum devices [6-8].

Excitons play a central role in photogeneration in organic detectors and solar cells. The efficiency of the exciton dissociation process is directly related to molecular structure of the donor and acceptor molecules and the film morphology. In our work, we have focused on understanding the microscopic nature of these interactions in both fullerene and non-fullerene based junctions. We have developed quantum mechanical models coupled with molecular dynamics simulations to understand the role that morphology plays on the energy of the charge transfer state — i.e. the intermediate between exciton and free polaron — and ultimately its ability to generate free charge at a low expense of energy. We find that quantum confinement of the exciton by crystalline domains in dilute donor-acceptor blends can result in substantial energy shifts in the state, thereby impacting its binding energy.[1, 2] Further, we have developed models that quantitatively relate the energy loss in non-fullerene acceptors to the molecular structure itself. Ultimately, this understanding of exciton and CT state energetics has led to very high efficiency (>15%) organic solar cells, with prospects of reaching 20% in the not distant future.[3] The models, experiments and implications of these findings will be discussed in my presentation. Finally, if there remains time, I will discuss confinement effects in novel quantum well structures comprising a combination of organic and inorganic semiconductors, including 2D solids.[4]

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