Statement Of Research

Sujoy Ghosh

With the growing demand on enhanced functionality, and hence, size, speed, and power consumption becoming the most crucial factors for the next generation electronic devices, innovation in materials synthesis and modification becomes imperative. Till date, the unabated growth of electronic technology has been mainly achieved by dimensional scaling of the conventional complementary metal-oxide-semiconductor (CMOS) technology. However, as the device scaling continues to grow further, it is becoming more and more challenging to overcome the enhanced short channel effects such as high leakage current, low mobility, gate induced drain leakage (GIDL), and many more. Therefore, the conventional "Moore's Law" cannot be maintained further only by improving the conventional scaling technology alone, and eventually, additional new materials and transistor geometries are needed to address these challenges [1].

In this regard, one-dimensional and two-dimensional(2D) nanomaterials (such as carbon nanotubes, Graphene, MoS_2, WSe_2, $In_2 2Se_3$ etc.) due to their unique structure property correlation can provide viable solutions to these above-mentioned problems. Actual realization of future generation devices such as ultrafast photo detectors, highly efficient field effect transistor (FET), spin FETs etc. is possible utilizing these materials. Thus, understanding the fundamental properties of these material becomes essential to realize these next generation devices. Therefore, in the past I have developed significant expertise in understanding core properties of these materials that can be utilized for developing next generation devices.

PAST RESEARCH EXPERIENCES

ELECTRONIC TRANSPORT IN LOW DIMENSIONAL MESOSCOPIC SYSTEMS

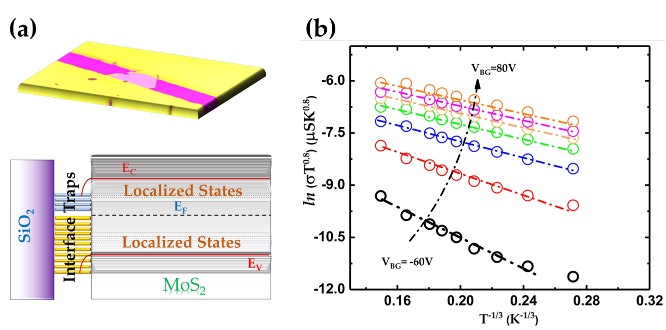

Figure 1.(a) Source-Drain contacted exfoliated MoS_2 flake on SiO_2 and the corrsponding schematic of the band-diagram (b)Temperature dependent conductance shows 2D VRH transport mechanism.

Mesoscopic systems are positioned in the middle-ground between the conventional macroscopic systems and the exotic nano-scopic systems and thus becomes very exciting and notoriously difficult to analyze. Thus, in modern technological context, understanding the fundamental charge transport mechanisms in mesoscopic systems are of critical importance to address the fundamental practical problems associated with the miniaturization of the electronic devices from µm to nm scale. Typically, mesoscopic systems contain disorders which in turn localizes the charge carriers and thus impedes electronic transport even in otherwise conducting materials. The presence of disorders creates localized states at various energies throughout the sample and the charge-carrier conduction occurs via hopping through these localized states. Since these localized states are distributed randomly throughout the system the typical conduction mechanisms can be often described by the variable range hopping (VRH) model. Despite of the negative impact on the electrical conduction, the presence of disorders can be utilized to tailor the electrical response. For example, an insulator with the Fermi level inside the gap. If these localized states are located close to Fermi level, then they can be utilized by the charge carriers for moving through the sample generating significant electrical response. In case of various low dimensional mesoscopic devices, these disorders often arise from extraneous sources, such as presence of charged impurities on the substrate, surface adatoms, grain boundaries etc. [2,3]. Some of my past studies involved understanding the fundamental nature of electronic conduction mechanisms in various mesoscopic devices utilizing various low dimensional nano-materials such as Graphene,MoS_2[4] etc.

PHOTO-CONDUCTION & DETECTION IN NANO-MATERIALS

Low dimensional materials, such as nanotubes, quantum dots, graphene and other 2D materials etc. exhibit diverse and intriguing physical phenomena that are very different from their bulk counterparts. The quantum size effect alters the electronic band structure significantly, leading to novel light-matter interactions and allowing for dramatic electrical control and efficient detection of light. Nonetheless, several device specific artifacts such as defects, light intensity, contact material, photo-thermoelectric effect etc. leads the photo-conduction mechanisms in low-dimensional materials especially rich and complex. In the past, I have studied the photo-current generation mechanisms and the role of these artifacts on their photo-detection capabilities. Some of these materials include mechanically exfoliated $CuIn_7Se_{11}$ photo-transistors [5],liquid phase exfoliated MoS_2 thin films [6], WSe_2, In_2Se_3 etc. .

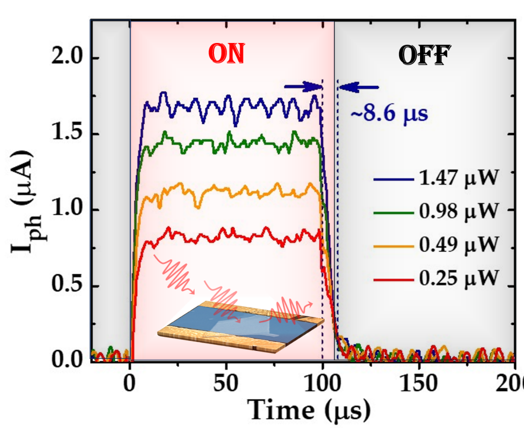

Figure 2.Fast photo-switching in multi-layer exfoliated $CuIn_7Se_{11}$ based photo detector[5].

FIELD EFFECT TRANSISTOR (FET) DEVICES BASED ON NANO-MATERIALS

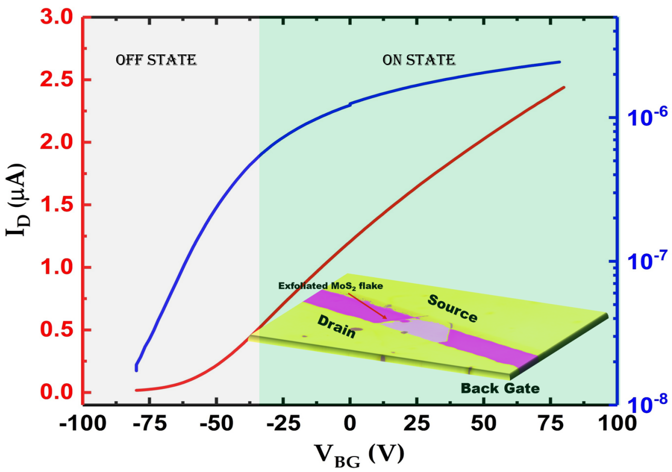

Figure3.Transfer characteristics of back-gated MoS_2 FET.Inset:Source-Drain contacted exfoliated MoS_2 flake on Si/SiO_2 .

So far, the silicon based conventional metal-oxide-semiconductor (MOS) FETs have been the key component for various electronic devices ranging from microprocessors to electronic sensors. Over the past few decades, significant development in microfabrication technology and integrated circuits has led to rapid growth in Si based electronics by miniaturizing the Si-FET channels even down to few nano-meters. However, the demand for flexible, bendable/wearable electronic applications poses the ultimate challenge and limitations for these solid-state Si based MOS transistors technology. In this regard low-dimensional nano-materials such as nano-wires, nano-tubes, 2D materials etc. based FETs have been envisioned as some of the prime candidates due to its unique mechanical behaviors with the capability to support a range of important flexible electronic applications, which would be difficult to achieve using conventional semiconductor materials such as Si or Ge. Additionally, some of these nano-scale materials such as Graphene, nanotubes etc. also provide superior electronic properties which can further revolutionize the performances of the nano-electronic devices. Thus, understanding the device properties of these nanomaterials under common experimental conditions is of critical importance for proper utilization of these in nanoscale FET devices. A sizable portion of my research experiences fall into exploring the device characteristics of low-dimensional systems, including experimental verification of novel device concepts for improved transistor performance, exploration of nano-materials, and nano-interfaces for future nanoelectronics applications.

ELECTROCHEMICAL ENERGY STORAGE APPLICATION UTILIZING NANO-MATERIALS

To meet the global energy demand and the associated challenges of global warming and limited fossil fuel reserve, environment friendly and more efficient energy storage devices are of critical importance. Among various energy storage systems, electrochemical capacitors (ECs), are especially attractive for use in portable electronic devices, electric vehicles etc. for their combined capabilities of providing high energy density as well as high power density and have very long lifetime of operation. ECs take advantage of near-surface charge storage mechanisms by forming an electrochemical double-layer capacitance to achieve much greater power density. In this regard, nano-materials offer unique advantages due to their high surface to volume ratio for the use of ECs electrode material. During my M.S. thesis, I have gained considerable experience on electrochemical energy storage application using some of these nano-materials such as MoS_2 [7] , functionalized Graphene [8] etc.

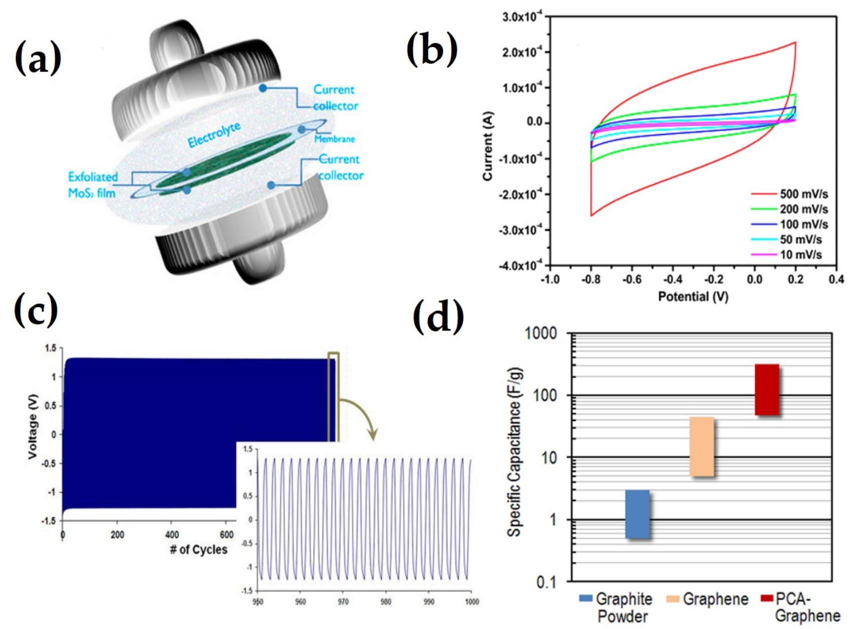

Figure 4.(a) Exploded view of the geometry used to prepare EDLC devices. (b) Cyclic voltammetry at various scan rates of a MoS_2 EDLC using KOH as the electrolyte [7] (c) Extended charge−discharge cycling of PCA-graphene electrode for testing the stability and reliability of the electrodes and (d) comparison of specific capacitances of devices made with graphite powder (starting material), graphene, and PCA-graphene electrodes [8].

ONGOING RESEARCH

NANO- MATERIALS BASED BIOSENSING DEVICES

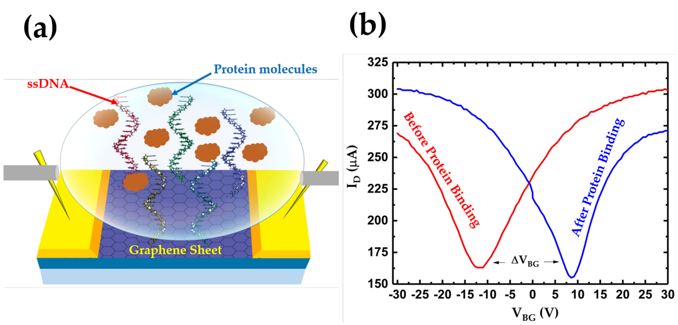

Figure 5.(a)Schematic representation of Aptamer based selective protein detection using Graphene FETs (b) Transfer characteristics of Graphene-FETs before and after protein binding[9].

The unique properties of low-dimensional materials such as large surface area, tunable energy band diagrams, a relatively high electron mobility, photoluminescence, stability in liquid media, relatively low toxicity, and intercalatable morphologies have led to significant research thrust for potential biosensing applications [10]. The major focus of this area lies in the development of probes for selective detection. So far, Graphene is extensively studied in bio-sensing research due to their inherent biocompatibility, structural flexibility, easy synthesis, high electrical conductivity and the extensive post-modification capability. However, the absence of band-gap in graphene often results in low sensitivity [11]. My current post-doctoral research work is primarily focused on developing aptamer based selective bio-sensors for detection of several protein molecules by exploiting the FET characteristics of Graphene and other atomically thin non-Graphene 2D layered materials such as MoS_2, black-phosphorous etc.

FUTURE RESEARCH INTEREST

As the family of 2D crystals is expanding day by day, a plethora of opportunities appear in areas ranging from exciting new physical phenomena to novel proof of concept device applications. With the amount and kind of experiences I have honed so far, I would like to focus in the specific areas as described in the following sections.

2D HETEROSTRUCTURE BASED OPTOELECTRONICS

Two-dimensional (2D) materials offer a platform that allows creation of heterostructures with a variety of properties. Held together by van der Waals forces (the same forces that hold layered materials together), such heterostructures allow a far greater number of combinations than any traditional growth method. Such heterostructures have already led to the observation of numerous exciting physical phenomena. The extended range of functionalities of such heterostructures yields a range of possible applications. For example, highest-mobility graphene transistors are achieved by encapsulating graphene with h-BN[12]. Similarly, photovoltaic and light-emitting devices have been demonstrated by combining optically active semiconducting layers and graphene as transparent electrodes[13,14]. However, the stacking of various 2D structures also leads to very rich and complex synergetic effects. One of my primary future research objectives is to develop various novel nano-optoelectronic systems such as solar cells,LEDs etc. based upon two-dimensional (2D) heterostructures and to investigate some of the fundamental synergetic effects such as doping control, contact formation, carrier mobility and other fundamental effects of heterogeneous integration of various monolayer or bilayer 2D materials.

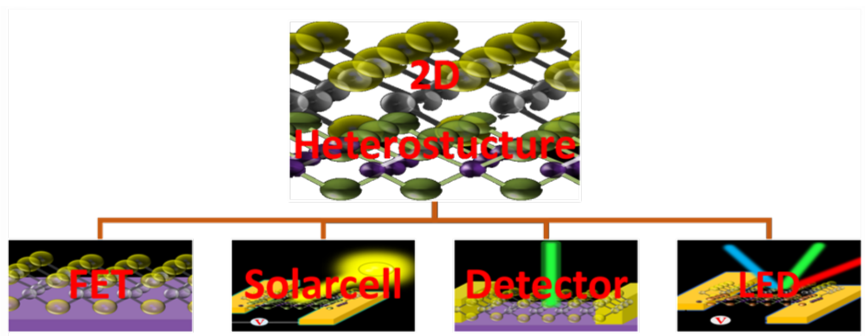

Figure 6.Schematic representation of the proposed plan for various applications of 2D heterostructure.

2D MATERIALS BASED FETS FOR FLEXIBLE ELECTRONICS AND SENSORS

Nano-scale electronic sensors are becoming increasingly important in our modern-day lives. Electronic sensors are fundamentally electronic devices which can convert the physical or chemical environmental changes such as radiation, motion, heat, chemical potential etc. into measurable output signals. Among several types of electronic sensors devices, FETs are the most commonly used. Even though FETs-based sensors have been well-developed, flexible version of such sensors remains a big challenge and requires new materials and new sensing designs. Two-dimensional (2D) materials such as graphene and transition metal dichalcogenides are promising candidates for FET-based sensors due to their flexibility, transparency and potential for high electrical performance. Additionally, due to atomically thin nature of 2D materials, their electrical properties are extremely sensitive to their atomic-scale structure as well as to their surfaces and interfaces with other materials. Specifically, defects, dopants, attached molecules can shift the Fermi level resulting in a measured change in current. In this regard, considerable number of studies on Graphene based FETs have shown potential promise for sensing functionalities on extended number of species (ranging from air molecule to selective biological species). However, since graphene has a zero band-gap, the transistors based on intrinsic graphene have a low on-to-off current ratio, resulting in high standby power dissipation, which limits their real circuit application. On the other hand, 2D non-graphene materials have almost all the necessary range of band gap values, they can be used for the design of a FET device. FET is characterized by high electron mobility and a high on-to-off ratio. Thus, integrating the 2D non-graphene material-based channel of FET with bio-sensing layers, one can expect the design of a complex bio-sensing device. Another significant feature of 2D non-graphene materials is that unlike graphene, many of them have either an intrinsic direct band gap in a bulk state or undergo the transition from indirect to direct semiconductors upon being scaled down to single layers. This opens up their application as a transducer for biosensors of the optical type of detection, where their strong light-matter interaction can be influenced by the interface-related biological actions producing significant change in their photo current response. At the same time, recent reports suggest that solid state metal-substituted DNA incorporated hydrogel based dielectric system at the graphene/electrolyte interface exhibit fast response time with high operational frequencies of 1MHz[15]. Therefore, by integrating some high mobility non-graphene 2D semiconductors such as WSe_2 based FETs on a flexible optically transparent substrate with solid state hydrogel based electrolytes can further pave the way for extremely fast optical bio-molecular detectors.

In future, I would like to dedicate my research efforts on the following aspects of this field.

- Build up theoretical collaboration to have a better understanding on the detection mechanisms and interactions between 2D nanomaterials and varieties of interfaces, molecules, and cells.
- Investigate miniaturization and functionalization of 2D material-based sensors to facilitate the fabrication of 2D material-based sensors in arrays on flexible substrates that can be used for highly sensitive, selective, and high-throughput sensing.
- Characterize and optimize the selectivity and stability of the 2D material-based sensors in real-time environment for in vitro or in vivo biological sensing applications.
- Develop the fundamental understanding of the impact of materials processing, structure, interfaces and surfaces on resultant sensing characteristics.
- Explore the possibilities of building advanced sensor architecture and sensing mechanisms based on 2D heterostructures.

STUDENT ENGAGEMENT AND FUNDING OPPORTUNITIES

In the long-term future, I hope to advise undergraduate students and graduate students at the M.S as well as doctoral level. Following the legacy of my mentors, I endeavor to participate in and establish a strong research team with the active engagement of graduate and undergraduate students. I would like to disseminate my future research projects across diverse student levels. The particular learning objectives for the undergraduate students will be material synthesis via mechanical exfoliation and wet/dry transfer of flakes on the flexible substrates, optical characterization such as Raman and AFM measurements. The graduate level students will be engaged more on gaining hands-on training on microscale FET device fabrication, building the necessary experimental setup and device characterization, manuscript writing etc.

My future research agenda in an exciting, vigorous, high-impact area of scholarship comprising the need for improved understanding in basic sciences as well as for future technology development. Due to the significance of my research, including its impact on the field, it will bring value to several national level funding agency's missions. In the immediate future,I would like to submit proposals to secure funding for large multi-year projects from the national level funding agencies listed below-

- NSF Faculty Early Career Development (CAREER) Program
- Army Research Office - ARO Young Investigator Program
- Research Corporation for Science Advancement, Cottrell College Science Awards
- Air Force Office of Scientific Research Young Investigator Program
- National Science Foundation (NSF) bio-sensing program which supports fundamental research in areas related to novel sensitive, discriminative, low cost, and easy to operate bio-sensing systems

REFERENCES

1. International Technology Roadmap for Semiconductors (ITRS,2012);`http://www.itrs.net/`

2. S. Ghatak, A. N. Pal, and A. Ghosh "Nature of Electronic States in Atomically Thin MoS_2 Field-Effect Transistors" ACS Nano, 2011, 5 (10), pp 7707–7712.

3. S. Najmaei et al. "Vapour phase growth and grain boundary structure of molybdenum disulphide atomic layers" Nature Materials,2013, 12, 754–759.

4. S. Ghosh, et al. "Universal ac Conduction in Large Area Atomic Layers of CVD Grown MoS_2", Phys. Rev. B,2014, 89, 125422.

5. S. Ghosh, P.D. Patil, M. Wasala, S. Lei, A. Norlander, P. Sivakumar, R. Vajtai, P. M. Ajayan, and S. Talapatra,Fast Photoresponse and High Detectivity in Copper Indium Selenide ($CuIn_7Se_{11}$) Phototransistors" 2D Materials,2017,2D Mater. 5 (1) 015001 .

6. S. Ghosh et al. "Ultrafast Intrinsic Photoresponse and Direct Evidence of Sub-gap States in Liquid Phase Exfoliated MoS_2 Thin Films" Scientific Reports,2015, 5, 11272.

7. A. Winchester,S. Ghosh, S. Feng, A.L. Elias, T. Mallouk, M. Terrones, and S. Talapatra "Electrochemical Characterization of Liquid Phase Exfoliated Two-Dimensional Layers of Molybdenum Disulfide" ACS Appl. Mater. Interfaces 2014, 6, 2125−2130.

8. S. Ghosh, X. An, R. Shah, D. Rawat, B. Dave, S. Kar and S. Talapatra "Effect of 1- Pyrene Carboxylic-Acid Functionalization of Graphene on Its Capacitive Energy Storage" J. Phys. Chem. C 2012, 116, 20688−20693.

9.S. Ghosh,N.I.Khan,E.Song"Selective Detection of a Protein Biomarker Utilizing a Large Area CVD-Grown Graphene-Based Field Effect Transistor"(Manuscript under preparation)

10.N. Chauhan, T. Maekawa, and D.N. S. Kumar "Graphene based biosensors—Accelerating medical diagnostics to new-dimensions" J. Mater.Res,2017,32(15), 2860-2882.

11.K. Shavanova et al. "Application of 2D Non-Graphene Materials and 2D Oxide Nanostructures for Biosensing Technology" Sensors 2016, 16, 223.

12.N.Petrone, T.Chari, I.Meric, L.Wang, K. L. Shepard, J. Hone"Flexible Graphene Field-Effect Transistors Encapsulated in Hexagonal Boron Nitride"ACS Nano,2015,9(9)8935-8959.

13.F. Withers, O. Del Pozo-Zamudio, A. Mishchenko, A. P. Rooney, A. Gholinia, K. Watanabe, T. Taniguchi, S. J. Haigh, A. K. Geim, A. I. Tartakovskii , K. S. Novoselov "Light-emitting diodes by band-structure engineering in van der Waals heterostructures"Nature Materials,2015 14, 301–306.

14.M.Shanmugam, R.Jacobs-Gedrim, E. S. Song, B.Yu"Two-dimensional layered semiconductor/graphene heterostructures for solar photovoltaic applications"Nanoscale, 2014,6, 12682-12689.

15. B.J Kim, S.H. Um, W. C. Song, Y.H. Kim, M.S. Kang, and J.H. Cho "Water-Gel for Gating Graphene Transistors" Nano Lett., 2014, 14 (5), 2610–2616.