

Energy and Spin Resolved Perpendicular Transport in Oxide and Graphene based Heterostructures

PhD Proposal
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1. Title of the Project

Energy and Spin Resolved Perpendicular Transport in Oxide and Graphene based Heterostructures.

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6. Abstract

Probing charge and spin transport over a wide energy spectrum gives important insight into fundamental excitations and transport characteristics that cannot be addressed by ordinary conduction at the Fermi energy. A few interesting examples in this direction are – (i) the half metal manganites which are transport half metals but only at the Fermi energy, (ii) graphene where the linear energy-momentum dispersion relation is valid only up to ~ 1 eV above and below the charge neutrality point (CNP), etc. In spite of the rich physics of transport at such energies ($> E_F$), they have remained relatively unexplored.

In this project, using a unique transport scheme, we will investigate the charge and spin transport at the nanoscale in different device structures over a wide energy range. We propose to do this using the technique of Ballistic Electron Emission (Magnetic) Microscopy. We will use two different device structures: (i) an epitaxial interface of a manganite with an oxide semiconductor and integrate it with a metal ferromagnet to study the energy and temperature dependence of the spin transport parameters and (ii) graphene/hexagonal boron nitride heterostructure on Si to study the energy dependence of charge transport in such heterostructures at the local scale and the tunability of its transport characteristics. Both the above areas have not been explored and our work is expected to contribute to useful insights into the energy resolved transport of charge and spin and will have important implications in the area of nanoelectronics in general and oxide spintronics and graphene electronics in particular.

7. Research Proposal

7.1. Introduction

The technique of Ballistic Electron Emission (Magnetic) Microscopy (henceforth referred to as BEEM/BEMM) offers the unique possibility to probe charge and spin transport at the local (nanometer) scale in buried layers and interfaces^{[1][2]}. It allows us to extract transport parameters such as the energy dependence of the spin-dependent attenuation length. It also provides information of the band alignments at the unbiased metal-semiconductor interface and their local homogeneity that is sensitive to parameters like disorder and doping at the local scale. The technique of BEEM uses the tip of the Scanning Tunnelling Microscope (STM) to locally inject unpolarized electrons with high kinetic energy into a metallic film that is deposited on a semiconducting substrate. The metal surface is grounded and a voltage V_T is applied to the STM tip with the tunnel current I_T kept constant using feedback. The energy of the injected electrons is given by eV_T and transport is thus by hot electrons. For spin dependent studies with BEMM, a spin valve structure is used that comprises of a sandwich structure of two ferromagnets separated by a normal metal layer (Fig. 1a). The first ferromagnet acts as a spin filter producing a spin-polarized current which after transmission in the spacer layer proceeds to the second ferromagnet of the spin valve. This acts as the analyzer of the transmitted spin polarization. The transmitted electrons are collected in the conduction band of the semiconductor (Fig. 1b) having a separate electrical contact. Collection in the semiconducting substrate is possible for those electrons that have retained sufficient energy and momentum to cross the Schottky barrier (ϕ_B) at the metal/semiconductor interface. Spin sensitivity is provided by an external magnetic field provided by an electromagnet.

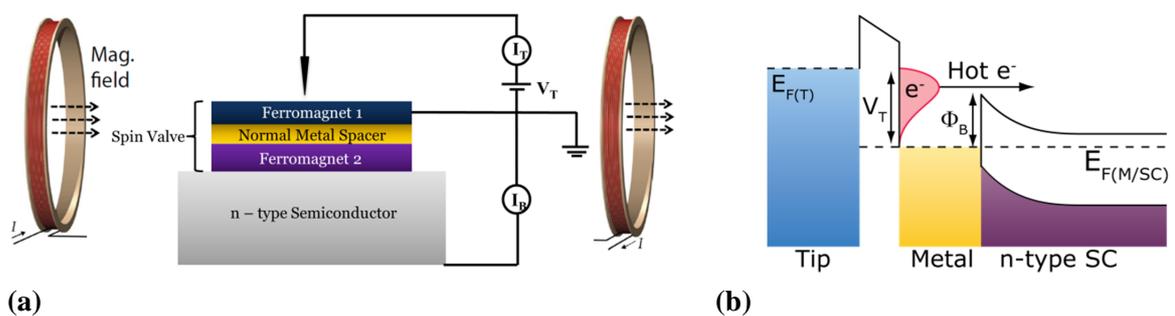


Figure 1: Schematic diagrams of (a) the BEMM experimental set-up and (b) the energy schematics of a typical BEEM experiment on metal-semiconductor interfaces.

Apart from the unique ability to probe spin transport at the nanoscale in buried layers and interfaces, another advantage of this technique is that the energy of the injected electrons (hot electrons) can be tuned over a wide range thus providing information of spin-transport and fundamental excitations not accessible by ordinary conduction at the Fermi energy.

Heterostructures of strongly correlated transition metal oxides like manganites and layered materials like graphene and hexagonal boron nitride (hBN) are important candidates for future electronic and spintronic devices beyond the CMOS era. Half-metal manganites and graphene are predicted to exhibit interesting properties at elevated energies ($> E_F$). For example, manganites like LSMO exhibit half-metallicity only at E_F , the linear dispersion relation of graphene is valid till energies of $\sim 1\text{eV}$ above the CNP. Thus, it will be relevant to investigate the transport of charge and spins over a wide energy range in these materials. This will provide useful insights into hitherto unknown properties of these materials that can have significant implications in the field of nanoelectronics. The BEMM technique employing hot electrons is an effective experimental tool to study energy and spin resolved transport in these materials and their heterostructures at the nanoscale. It will also allow us to quantify transport parameters as the energy dependent attenuation length and to study the different scattering mechanisms of hot electrons (elastic, inelastic, phonon and other quasi-elastic scattering processes due to magnons). The influence of such scattering processes to transport in a vertical heterostructure device is expected to be different at energies beyond E_F .

In this project, we propose to study the transport characteristics of charge and spin in two different materials and their heterostructures employing the BEMM technique in a perpendicular geometry at the nanoscale:-

- (i) The epitaxial interface of the manganite LSMO with an oxide semiconductor (Nb:STO) along with its integration in a spin valve and
- (ii) Graphene-hBN heterostructures on silicon.

7.1.1. LSMO

$\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$ (LSMO) belongs to the family of doped mixed-valance manganese perovskites with the general formula $\text{Ln}_{1-x}\text{A}_x\text{MnO}_3$ (where Ln is a trivalent rare-earth element and A is a divalent alkaline-earth element). The basic LSMO perovskite crystal structure is shown in Fig.2(a).



Figure 2: (a) Basic crystal structure of LSMO perovskite. The oxygen octahedron around the mixed valance $\text{Mn}^{3+}/\text{Mn}^{4+}$ is also shown. (b) Schematic view ^[4] of the band structure of $\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$. The level diagram on the left corresponds to that of an isolated Mn ion in an octahedral crystal field.

Due to the small size of the partially filled d -orbital of Mn, the overlap with other orbitals is reduced but the interaction between the electrons within the orbital is enhanced. This causes strong correlations in LSMO. The five d -orbitals of an isolated Mn ion are split into a t_{2g} triplet and an e_g doublet due to crystal field in the ideal perovskite structure. The degeneracy of the t_{2g} triplet and e_g doublet is further lifted by lattice distortions (Jahn-Teller distortions) lowering the crystal symmetry. The oxygen $2p$ states are fully occupied for both spin states and the electronic structure near the Fermi level is determined by the hybridization between the bands associated to the majority spin Mn e_g states and the oxygen p states. An insulating band gap separates the minority spin states and the oxygen $2p$ band, causing the LSMO spin-polarized density of states to have only majority carriers at the Fermi level. Hence LSMO is a half metal unlike a conventional ferromagnet. The Curie temperature (T_c) of LSMO is close to room temperature (~ 280 - 300 K) and this makes it an interesting material for spintronic applications. An explanation for the metallic conduction below T_c and insulating behaviour above T_c is provided by the “double exchange” (DE) mechanism^[5]. Charge transport is mediated by the hopping of electrons between adjacent Mn³⁺ and Mn⁴⁺ e_g states along the Mn³⁺-O²⁻-Mn⁴⁺ chains with the hopping probability being maximum when the manganese spins are parallel to each other. However, to understand the full picture of conduction and ferromagnetism in LSMO, one has to take into consideration the competing double-exchange and super-exchange interactions, charge (orbital) ordering instabilities and strong coupling with lattice deformations.

The hot electron attenuation length in LSMO deposited on n-type semiconducting Nb-doped SrTiO₃ (Nb:STO) was extracted in a recent study employing BEEM technique^[6]. We propose to use identical Schottky interfaces as in ref. 6 but now to integrate a second ferromagnet in a spin valve configuration as shown in Fig. 3. With this device structure, we propose to study spin-resolved hot electron transport across LSMO – Nb:STO interface and extract the majority and minority spin attenuation lengths in LSMO. The temperature dependence of the transport characteristics and lateral inhomogeneities in transport will also be studied at the nanoscale.

7.1.2. Graphene based heterostructures

Graphene possesses several unique fundamental physical properties leading to exceptional charge^[7] and spin transport^[8] characteristics. The exceptional electronic properties of graphene is attributed to its linear dispersion for $|E| < 1$ eV around the Dirac points (K, K') at the vertices of the hexagonal Brillouin zone (Fig. 2). The charge carriers in this energy regime are relativistic massless Dirac fermions having Fermi velocity of $\sim 10^6$ m/s. The high carrier mobilities and long spin relaxation lengths (~ 10 μ m) make graphene one of the most studied materials for development in electronics and spintronics. The past decade has witnessed extensive research on graphene and its in-plane charge and spin transport characteristics. One of the few areas relevant for graphene electronics which still remains to be explored is the charge and spin transport of electrons

and holes in graphene at high energies (above/below the Fermi level) using vertical graphene nanodevices and heterostructures.

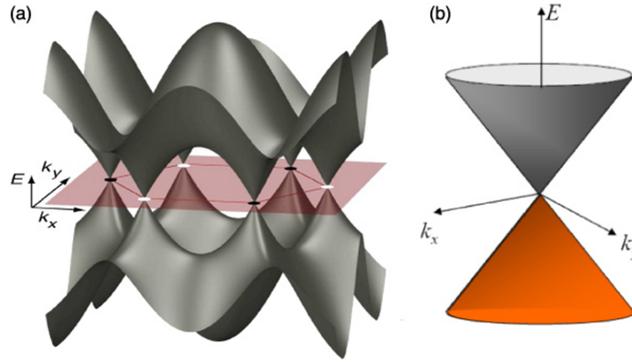


Figure 2: Graphene band structure. **(a)** Three dimensional band structure. Adapted from C.W.J. Beenakker, *Rev.Mod.Phys.*, **80** (2008) 1337. **(b)** Zoom into low energy dispersion at one of the \mathbf{K} points shows the electron-hole symmetric Dirac cone structure .

Conventional devices operate over a wide energy spectrum for various electronic and optoelectronic applications. At such energies, electron transport is dominated by hot electrons for which the physics is distinctly different from the transport at the Fermi energy. In this project, we propose to study hot electron (and hole) transport in graphene based heterostructures and study the device performance at energies typically $> 1V$. The unique band structure of graphene, in particular, will make it appealing to study energy dependent transport beyond the CNP in graphene heterostructures.

Graphene – Silicon interface

One of the most crucial challenges in graphene transistors with conventional device structures has been the low on/off current ratio (I_{on}/I_{off}). In a recent research, on/off current ratios as high as 10^5 was demonstrated in a three-terminal device, known as the graphene variable-barrier barristor, employing the Schottky barrier formed at the graphene-silicon interface ^[9]. Through a gate electrode, the work function of graphene was tuned which resulted in a variable Schottky barrier at the graphene-Si interface. The Schottky barrier formed at the graphene-silicon interface can be utilized for a number of technological applications like graphene barristor ^[9], solar cells ^[10], spin transport study, etc. We have preliminary results on hot carrier transport through graphene – n type Si and graphene – p type Si interfaces. Besides a successful fabrication of such vertical devices, we have also made a first observation of hot electron and hot hole transport in these devices. We have extracted the local Schottky barrier height (SBH) at the interface. We propose to continue this research and study hot electron transport at the nanoscale using exfoliated, CVD and epitaxial graphene on Si. Through this study we can investigate the lateral inhomogeneity in SBH at different positions of the graphene-silicon interface. The reverse scattering BEEM (R-BEEM) technique will also allow us to study the scattering mechanism of hot electrons in graphene and its dependence on energy of the carriers and the temperature.

Graphene – hBN heterostructures

Graphene has been isolated on SiO₂ substrates for most of the studies on graphene's electronic properties. The main advantage of SiO₂ is that monolayer regions of graphene on SiO₂ can be easily identified using optical microscopy. However the surface of SiO₂ is characterized by high roughness and trapped charges in the oxide, both of which proves to be detrimental to graphene's electronic properties since the impurity-induced charge traps electronically break up graphene into electron- and hole-doped puddles^[11] at low charge density. Recently, high quality graphene devices have been demonstrated on hBN^[12]. Hexagonal boron nitride is a wide-bandgap electric insulator^[13] with a planar structure and ultra-flat surface. The atomic structure of hBN is similar to that of graphene but with 1.8% longer lattice constant^[14]. hBN exhibits ionic bonding and is thus free of dangling bonds and charge traps at the surface. Highest charge mobility has been demonstrated in graphene on hBN as compared to any other substrate along with narrow Dirac peak resistance widths, which indicate reduced disorder and charge inhomogeneity^[12]. Field effect tunneling transistor based on vertical graphene heterostructures^[15] has been reported recently which employ hBN as a vertical transport barrier placed between two graphene electrodes.

We propose to first investigate the characteristic of hot electron transport through hBN-silicon interface by tuning the barrier height by using an additional gate electrode at the Schottky interface and also by varying the thickness of hBN. Subsequently, we will study hot electron transport through graphene isolated on hBN at the nanoscale using BEEM. By this study, we will be able to investigate hot carrier transport perpendicular to the plane of hBN and the scattering mechanisms at the interfaces. It will also reveal lateral (in)homogeneity of hot electron transmission through graphene-hBN heterostructures. We can also comment on the stacking of graphene on hBN by observing distinct Moiré patterns^[16] by STM. This study can be extended to other graphene-based heterostructures employing layered materials like MoS₂^[17] and will be useful for developing graphene based nanodevices.

7.2. Research Questions

- Q1.** What are the majority- and minority-spin attenuation lengths in the half-metallic manganite LSMO? It is known from the band structure of LSMO that half-metallicity does not persist at higher energies. It will thus be important to probe transport at higher energies which will be relevant for designing oxide electronic devices. How is the spin transport dependent on temperature?
- Q2.** What is the nature of the local Schottky barrier formed at the graphene-Si interface? How will the intrinsic doping in Graphene affect the band alignment at the Gr/Si interface? On what factors would the transport of hot electrons in a single atom thick graphene interface with Si depend on? Can we probe ballistic transport in graphene using such interfaces? As we can also study scattered carrier transport in the same device structure using BEEM, it will be important to see if the transport of scattered carriers in graphene is different from that in conventional metals. What will be the consequence of the small density of states close to CNP to charge transport? Will electric field modulate the transport

characteristics, graphene being just one atom thick? Are there lateral variations in the SBH at the nanoscale? Will the different hot electron scattering contributions viz. elastic and inelastic be different in graphene as compared to conventional metals?

Q3. What are the characteristics of hot electron transport at the nanoscale through hBN-Si interface and through graphene-hBN-Si heterostructure? Can the transport properties be altered by tuning the barrier height by applying a gate voltage by the Si electrode? What is the effect of such bias on the tunneling density of states and Fermi level in graphene?

Q4. What is the energy dependence of hot electron transport through graphene-hBN-Si heterostructure? Does the parabolic band structure of graphene reveals itself at high energies ($> 1\text{eV}$) of the injected carriers? What is the homogeneity of the transport at the nanoscale in such heterostructures? What can we comment about the different scattering processes in this heterostructure by studying the characteristics of scattered carrier transport?

7.3. Approach and Methods

7.3.1. To address **Q1**, we will use the device geometry as depicted in Fig. 3.

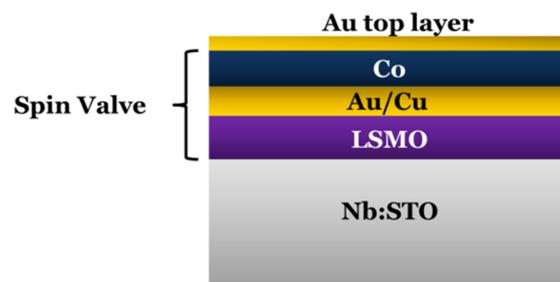


Figure 3: Schematic diagram of the spin valve device to study attenuation length of majority and minority spins in LSMO .

Nb-doped SrTiO_3 is a n-type semiconductor that will be used as the collector for the spins traversing the spin-valve structure fabricated on top of it. The advantage of using Nb:SrTiO₃ as the substrate material is that it has a very small lattice mismatch with LSMO ($\sim 1.3\%$) and thus LSMO grows epitaxially on it. A monolayer of SrMnO₃ will be first grown on a TiO₂-terminated Nb:SrTiO₃ (001) substrate (Nb: 0.01% wt.) in order to increase the interface dipole density across LSMO-Nb:SrTiO₃ interface for enhancing the SBH and suppressing the reverse bias leakage^[18]. The bottom ohmic contact is obtained by ultrasonically soldering indium on the Nb:SrTiO₃. LSMO (001) films will be deposited on top of this substrate by pulsed laser deposition (PLD). The deposited layer thickness will be controlled by reflection high-energy electron diffraction (RHEED) intensity oscillations. A non-magnetic metal layer of Au or Cu will be deposited on top

of LSMO followed by a ferromagnetic layer of Co. The choice of Co is primarily because it has a higher coercive field as compared to LSMO thus clear magnetic switching is expected in a spin valve structure. Finally, a thin layer of Au will be grown as the top layer which will prevent the Co layer from atmospheric oxidation. It is known from previous work in our group that 3-4 nm of Co film and 7 nm Au spacer produces 75% spin polarization of electrons at these energies ^[19]. These spin polarized electrons will be injected at the Au-LSMO interface and after spin transport in LSMO, will be collected at the Schottky interface with Nb:STO.

In order to determine spin majority and spin minority hot electron attenuation lengths in LSMO, we will fabricate several devices with varying LSMO thickness but keeping the thickness of other layers constant. Using the technique of ballistic electron magnetic microscopy (BEMM), a magnetic field can be swept to drive the spin valve from parallel (P) to anti-parallel (AP) states (and *vice-versa*). The BEMM current can be plotted as a function of the applied magnetic field keeping the tunneling bias voltage and tunneling current constant. A magnetic hysteresis loop is expected to be observed with a larger BEMM current in the P state (I_P) than that in the AP state (I_{AP}) and the measure of this difference is called the magnetocurrent (MC) which is defined as:

$$MC = \frac{I_P - I_{AP}}{I_{AP}} \times 100\% \quad (1)$$

The tip bias (V_B) can be swept and the BEMM current can be recorded for both P and AP states and thus we can determine the dependence of the magnetocurrent on the tip bias (energy of the injected electrons).

Hot electron attenuation lengths for majority-spins and minority-spins can be extracted from the P and AP BEMM transmission values obtained for different LSMO thicknesses. BEMM transmission in the parallel and anti-parallel states can be expressed as:

$$I_P \propto T_{FM1}^M T_S T_{FM2}^M + T_{FM1}^m T_S T_{FM2}^m \quad (2)$$

$$I_{AP} \propto T_{FM1}^M T_S T_{FM2}^m + T_{FM1}^m T_S T_{FM2}^M \quad (3)$$

where T^M and T^m refer to the transmission of the majority (M) and minority (m) hot electrons in the ferromagnetic layers (FM) respectively, and T_S is the transmission in the spacer (non-magnetic; NM) layer. The bulk transmission depends exponentially on each of the FM and NM layers according to the relation:

$$T \propto e^{-d/\lambda} \quad (4)$$

where d is the thickness and λ is the hot electron attenuation length of the layers (NM and FM). Since the thicknesses of the Co FM layer and Au spacer layer will be kept constant, relations (2) and (3) can be simplified to:

$$I_P = A \exp\left(-\frac{d_{LSMO}}{\lambda_M}\right) + B \exp\left(-\frac{d_{LSMO}}{\lambda_m}\right) \quad (5)$$

$$I_{AP} = B \exp\left(-\frac{d_{LSMO}}{\lambda_M}\right) + A \exp\left(-\frac{d_{LSMO}}{\lambda_m}\right) \quad (6)$$

where A and B are fitting constants which are related to the transmission of majority-spins and minority-spins in the other layers including the respective interfaces. Thus the attenuation lengths of majority-spins and minority-spins in LSMO can be extracted from the fitting of the data in the I_P vs. d_{LSMO} and I_{AP} vs. d_{LSMO} plots.

The T_C of such thin LSMO films vary from 280 K to 300 K. At $T < T_C$, ferromagnetic ordering sets in from a paramagnetic phase. Whether this leads to an increased BEMM transmission is also what we would like to probe by temperature dependent studies. We can also study the ferromagnetic ordering in LSMO spin valves as we cool the devices using the magnetic imaging capabilities of the technique.

7.3.2. To address questions **Q2** and the hBN-Si interface mentioned in **Q3**, we will fabricate the following device schemes:

We use n-doped Si substrates with 300nm of SiO_2 layer on top and Cr/Au back contact. The SiO_2 is etched off by BHF in the pattern of a $150\mu\text{m}$ diameter hole. Graphene or hBN is transferred onto this region and a top Au contact is deposited (Fig. 4).

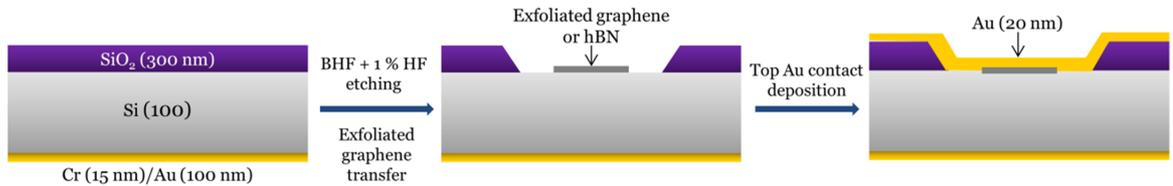


Figure 4: Schematic diagram showing the fabrication steps.

The energy schematic of the Au-graphene-nSi device is depicted in Fig. 5a. When the STM tip is brought close to the top surface (Au) and a negative bias applied, electrons are locally injected from the tip to the metal with a distribution of energy close to the Fermi level of the tip, which is eV_T above the Fermi level in the Au film (V_T being the tip bias). It is known that a 3-4 nm of Au film can preserve efficient transport of hot electrons; however it is not known if the same can be said for graphene, hence our first experiments will be with a thin Au film on top of graphene. The hot electron energy and flux can be tuned by varying the tip bias and the tunneling current respectively. Thus, by tuning the tip bias, we can access different energy states in graphene. After a certain threshold, the injected hot electrons are collected by n-Si. This threshold corresponds to the local Schottky barrier height (SBH) at the graphene/n-Si interface. We can also study the

scattering mechanism of the injected carriers in graphene by the technique of reverse scattering BEEM (R-BEEM). In this technique, hot holes are injected by the tip which undergo inelastic scattering in graphene and thereby generates secondary electrons. Among these secondary electrons, those having sufficient energy to cross the barrier at the graphene-nSi interface will be collected. The characteristics of R-BEEM spectra give us information about the scattering mechanisms of the hot carriers.

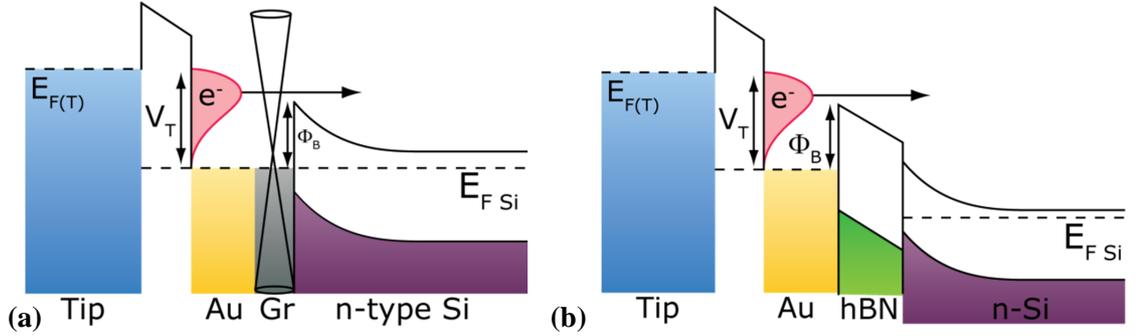


Figure 5: Schematic diagram depicting the energy schematics of (a) Au/Graphene/n-Si and (b) Au/hBN/n-Si heterostructures.

In case of the Au/hBN/n-Si heterostructure, the energy schematic is depicted in Fig. 5b. This heterostructure should behave as a MIS heterojunction. This opens up the possibility to apply a gate voltage across the Au film and n-Si (similar to the one depicted in Fig. 6) that can tune the energy barrier (Φ_B) in hBN. The BEEM transmission will also reflect the lateral homogeneity of the interfaces. hBN exhibits planar structure with ultra-flat surfaces. Moreover, hBN is devoid of dangling bonds and trapped charges at the surface since it exhibits ionic bonding. Hence it will be interesting to compare the results with typical MOS structures where the insulating layers are oxides like SiO_x which exhibit high roughness and trapped charges. Thus, MIS transistor operation can be demonstrated at the nanoscale using hBN as the insulator by the BEEM technique.

7.3.3. To address the questions on graphene-hBN heterostructures mentioned in **Q3** and **Q4**, we will integrate the heterostructure on n-Si.

The device geometry is shown in Fig. 6. van der Waals (vdW) assembly process^[20] will be used to fabricate the hBN-graphene stacks. This technique utilizes van der Waals adhesion to assemble heterostructures of graphene with other layered materials without exposing the interfaces to polymers. The hBN-graphene stack is then transferred on n-Si such that we have a MIS configuration with graphene serving as the metal, hBN as the insulator and n-Si as the semiconductor.

The BEEM transmission I_B will be studied as a function of the tip bias V_T which will reflect the energy dependence of hot electron transport through this heterostructure along with the different scattering processes and lateral (in)homogeneity of hot electron transport at the nanoscale. Further modification of the device operation can be implemented by introducing a gate bias V_G (as shown in Fig. 6).

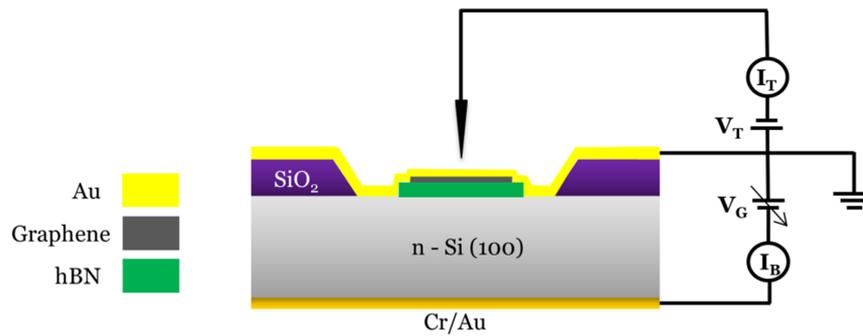


Figure 6: Schematic diagram of the Au/Gr/hBN/n-Si device. A gate bias (V_G) at the collector interface will tune the barrier height of hBN.

The tunneling density of states in graphene as well as the barrier height across hBN can be tuned by changing V_G . It will be interesting to study how V_G affects the barrier height and thus the transport characteristics of the hot electrons. The dependence of the transport properties on temperature can also reveal whether the barrier behaves as a tunnel or Schottky barrier. This study will provide valuable insight for development of hot electron transistors and nanodevices based on graphene heterostructures.

7.4. Work Plan

Period	Activity
Year 1	<ol style="list-style-type: none"> 1. Literature study and learning additional experimental techniques required for the project (PLD, SQUID, etc.). 2. Growth of LSMO on Nb:STO substrates by PLD. Establishing a device fabrication protocol including photolithography mask fabrication. 3. Optimization of the growth process and characterization of the oxide devices using AFM. 4. Estimating the SBH for LSMO-Nb:STO interfaces. 5. Integration of Co with a spacer layer on LSMO will be done for the first time and hence the process will be optimized. The spacer layer can either be Au or Cu since these metals have already been used in our group as spacer layers with Co and the respective spin polarization is known. Spin valves with both Au and Cu spacer layers will be fabricated, compared and characterized.

<p style="text-align: center;">Year 2</p>	<ol style="list-style-type: none"> 1. Fabrication of devices with different thicknesses of LSMO. 2. Magnetic characterization of such heterostructures using SQUID. 3. BEMM studies on the Co-LSMO spin valves to estimate majority and minority spin attenuation lengths in LSMO. 4. Temperature dependent BEMM spectroscopy and imaging to probe the local transition from disordered paramagnetic phase to ferromagnetic ordering in LSMO.
<p style="text-align: center;">Year 3</p>	<ol style="list-style-type: none"> 1. Fabrication of graphene-Si devices. 2. Fabrication of hBN-Si devices. 3. Optimizing the process of locating small structures by the STM tip through designing of EBL markers. 4. BEEM and reverse scattering BEEM studies on graphene-Si and hBN-Si devices for extracting SBH and transport characteristics. 5. Studying the effect of gating in the hBN-Si devices.
<p style="text-align: center;">Year 4</p>	<ol style="list-style-type: none"> 1. Fabrication of the graphene-hBN heterostructures and integrating with Si. 2. STM on graphene-hBN heterostructures can reveal the lattice orientation of graphene on hBN by observing distinct Moiré patterns. 3. BEEM studies on this heterostructure to probe hot electron transport. 4. Exploring the possibility of gating this heterostructure and probing its effect on tuning the work function and carrier density in graphene as well as the hBN barrier height which will be reflected in the BEEM transmission. 5. Thesis writing.

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8. Infrastructure and Financial Support

- The BEEM system existing in the group of Prof. Tamalika Banerjee will be used for this project.
- Fabrication of the devices will be carried out at the NanoLab Groningen and Physics of Nanodevices (FND) cleanroom at the Zernike Institute for Advanced Materials.
- Growth of LSMO on Nb:STO will be done at the PLD facility of Prof. Beatriz Noheda, at the Zernike Institute for Advanced Materials.
- Graphene, hBN, will be provided by Prof. Bart van Wees' group and HQgraphene (<http://www.hqgraphene.com/>).
- Silicon wafers and Oxide substrates will be required and purchased for this project. Besides, UV photolithography mask will be designed and prepared within the Nanolab consortium in the Netherlands. Travel budget for the applicant for attending conference is also included in the running budget.

Budget summary (in k€)

	2014 (1/3)	2015	2016	2017	2018 (2/3)	TOTAL
<i>Personnel</i>						
PhD student	17	51	51	51	34	204
Personnel (costs)	17	51	51	51	34	204
Running budget	2.5	10	10	10	10	42.5

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Burdwan – 713101
West Bengal, India

Email: K.S.DAS@student.rug.nl

Nationality: Indian

• EDUCATIONAL QUALIFICATIONS

1. **Master of Science (MSc)**, *Nanoscience (Topmaster Programme)*, Zernike Institute for Advanced Materials, University of Groningen, The Netherlands. *September 2012 – August 2014 (to be completed)*. CGPA: 8.15 (calculated till November 2013)
2. **Bachelor of Science (BSc)** in *Physics (Honours)* from St. Xavier's College, Kolkata (University of Calcutta), India. *July 2007 – June 2010*. First Class, 72.5% marks in Physics Honours.
3. **Higher secondary education** from St. Xavier's School, Burdwan, India. *June 2005 – May 2007*. *Indian School Certificate Examinations – 2007*, Percentage marks: 91.8%.
4. **Secondary education** from Holy Rock School, Burdwan, India. *Indian Certificate of Secondary Examination – 2005*, Percentage marks: 90.6%.

• PROJECTS

1. Research Project in Single Molecule Biophysics research group of Prof. Dr. Antoine M. van Oijen, Zernike Institute for Advanced Materials (March – June 2013): *Single molecule study of the kinetics of hemifusion of influenza virus with liposomes of different radii of curvatures using Total Internal Reflection Fluorescence Microscopy (TIRFM)*.
2. Master Thesis Project in Physics of Nanodevices (Spintronics in functional materials) research group of Prof. Dr. Tamalika Banerjee, Zernike Institute for Advanced Materials (September 2013 – present): *Hot carrier transport across graphene – silicon interfaces using Ballistic Electron Emission Microscopy (BEEM)*.

• TALKS, CONFERENCE POSTER & REVIEW ARTICLE

1. *Kinetics of Hemifusion of Influenza Virus with Liposomes of different Radii of Curvatures using Total Internal Reflection Fluorescence Microscopy (TIRFM)*, talk at Nanoscience Symposium – 2013, Zernike Institute for Advanced Materials, University of Groningen, June 2013.
2. *The Large Hadron Collider*, a public talk at St. Xavier's College, Kolkata, November 2008.

3. *Separation of Semiconducting and Metallic Single-Walled Carbon Nanotubes*, a review paper (course work) under the guidance of Prof. Dr. Maria A. Loi, Photophysics and Optoelectronics group, Zernike Institute for Advanced Materials, August 2013.
4. *Unconventional Transport Characteristics in a Vertical Device with Graphene*, R. Ruiter, K. S. Das, S. Parui, P. J. Zomer, B. J. van Wees, and T. Banerjee, poster presented at Physics@FOM conference, Veldhoven, The Netherlands in January 2014.

- **WORK / TEACHING EXPERIENCE**

Taught Physics, Chemistry and Mathematics to high school students at Burdwan Model School, India, *February 2011 – March 2012*.

- **EXPERIMENTAL & INSTRUMENTATION SKILLS**

1. Optical Microscopy (including confocal and fluorescence microscopy techniques)
2. Silicon wafer processing and device fabrication
3. Graphene transfer techniques
4. Atomic Force Microscopy (AFM), Scanning Tunneling Microscopy (STM), Scanning Electron Microscopy (SEM), Ballistic Electron Emission Microscopy (BEEM)
5. Electron beam physical vapour deposition systems
6. Experience in working in cleanroom, *NanoLabNL* (ISO 6), Groningen.

- **LANGUAGE & COMPUTER SKILLS**

1. **Languages:** English (Fluent): International English Language Testing System (**IELTS**) Band Score : **8.0**, Bengali (Fluent), Hindi (Fluent).
2. **Computer Skills:** Programming: C, JAVA, FORTRAN, Matlab, SQL and HTML
Softwares: Origin, MSOffice, EBL design software (Raith), Adobe InDesign & Illustrator

- **EXTRACURRICULAR ACTIVITIES**

1. Associate Editor of the annual Department of Physics Magazine, *HORIZON (2009-10)*, at St. Xavier's College, Kolkata.
2. Photography: Participated in photography exhibitions in college.
3. Participated in several Debates and Quiz competitions in school and college.

- **ACHIEVEMENTS**

1. Received the most prestigious student award in Holy Rock School, Burdwan: "*MASTER HOLY ROCK-2005*".
2. School Topper in Indian School Certificate Examinations-2007.
3. Ranked 4th (top 5 %) in the final exams of BSc Physics Honours at St. Xavier's College Kolkata.
4. Recipient of full scholarship awarded by The Zernike Institute for Advanced Materials for academic excellence to pursue the two years Topmaster Nanoscience (MSc) programme at the University of Groningen, The Netherlands.



Declaration of hospitality and financial support for research costs

Appendix to the Proposal for a PhD research position
in the NWO Graduate Programme Advanced Materials, deadline 2 Feb. 2014

Name of the applicant: KUMAR SOURAV DAS

Title of the proposal: ENERGY AND SPIN RESOLVED PERPENDICULAR TRANSPORT
IN OXIDE AND GRAPHENE BASED HETEROSTRUCTURES.

By signing this document the staff member declares that she/he is willing to host and supervise the PhD research project that is mentioned above. In addition, the staff member declares that she/he has and makes available the materials, infrastructure and the funding that is needed for covering the research costs (the costs in addition to the salary of the PhD student some funding for travel and training), as described in the proposal.

The signing staff members must be affiliated with the Zernike Institute for Advanced Materials (including the associate members).

Signatures

Applicant (the student applying for the PhD grant)

Date: 31/01/2014 Name: Kumar Sourav Das

Signature:

Daily PhD supervisor (only needed if applicable, in case of supervision by an assistant professor or UD/UHD without ius promovendi)

Date:

Name:

Signature:

1st Promotor (staff member with ius promovendi)

Date:

Name:

Signature:

31/1/2014. TAMALIKA BANERJEE