Research Summary

Mesoscale interactions such as spin-orbit interaction, nuclear hyperfine fields, and localized states control charge and spin transport in many condensed matter systems. Therefore, understanding and controlling these mesoscale interactions at the correct length scale is essential to build efficient light emitting diodes (LEDs), to harvest more electricity from solar energy, and to build an emerging class of storage devices. My research plan focuses on measurements of charge and spin dynamics using electron spin resonance at nanoscale. The broader goal is to develop detailed understanding of mesoscale interactions that control device properties. Therefore, the information about these mesoscopic physical processes will lead to improved device performance and functionalities.

Project-1. New method to probe mesoscopic environment of electron using spin-resonance and near field scanning optical microscopy (NSOM).

Harvesting sunlight via photovoltaic effect has the potential to solve the ever-increasing demand for energy if efficiency and cost can reach 20% and $0.50/W respectively as given by DOE, "SunShot 2020 Baseline Targets". Recombination of photogenerated charge carriers is central factor limiting the efficiency, and the relative spin-orientation of photogenerated charge carrier pairs (electrons and holes) controls the recombination rate. As photogenerated carriers slowly move through a disordered energy landscape in amorphous semiconductors used in solar technologies, tiny spatial variations in mesoscopic environment of charge carrier pairs relieve spin blocking (i,e transforming into antiparallel from parallel spin orientation of charge carrier pairs) and therefore, enhance recombination rate. Many mesoscale interactions like spin-orbit interaction, and hyperfine interaction and localized defect states influence the spatial variation in mesoscopic environment of photogenerated charge carrier pairs.

The proposed project is to identify and evaluate the role of mesoscale interactions and role of defects on inefficiency and degradation mechanisms of several photovoltaic materials at nanoscale.

Proposed experimental method: Fig.1 illustrates a near field scanning optical microscope (NSOM), modified to support spin resonance experiments. Charge carriers will be photo-generated within the optical spot size of the NSOM fiber (~30nm [1]). Many of these charge carriers will recombine and emit photo-luminescence characteristic of their local environment. Photo-luminescence (PL) will be collected using the same fiber. Since, the recombination rate depends on relative spin orientation of carrier pairs, therefore, introducing spin manipulation via spin-resonance will yield locally measured optically detected magnetic resonance spectra. Therefore, local nuclear hyperfine fields, g-factor and g-factor anisotropies will be quantified from magnetic resonance characteristic such as linewidth. NSOM fiber will scan and measure spatially resolved optically detected magnetic resonance spectra over macroscopic area. These

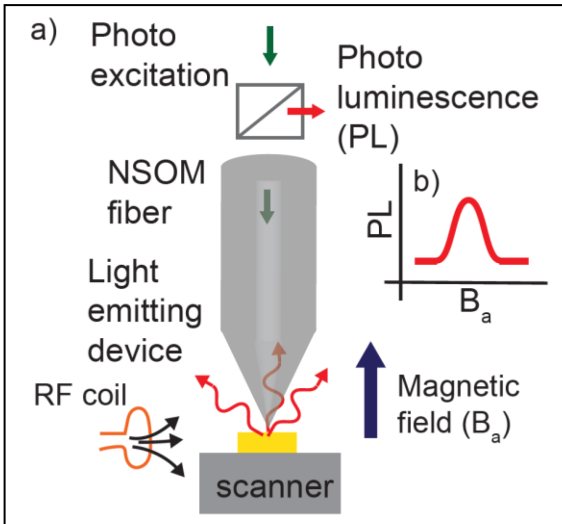

Fig.1. (a) Experimental setup contains NSOM fiber attached to a tuning fork based AFM (not shown). Sample is sitting on X-Y scanning module. RF field will be applied using a coil. Static magnetic field will be applied using an electromagnet. Photo-luminescence will be collected using the tapered fiber. (b) illustration of the change in PL during magnetic resonance sweep.

measurements will help to uncover the distribution localized states at nanoscale and variation of local environments (hyperfine fields) and their involvement on local and global spin-dependent charge transport. Also, the spatially resolved magnetic resonance measurements will be used to quantify the correlation between domain sizes and defect density and their role in device inefficiency and degradation.

Goals: The goal of the proposed project is to identify key mesoscale interactions and how these interactions influence the device performance locally and globally. Using scanning probe, this project will yield correlation map between morphological variations and mesoscale interactions. This correlation map will help us to identify key bottle necks that causing inefficiency.

In addition, the proposed measurement will identify and measure chemical identity of localized states that influences charge and spin transport. This measurement will also reveal that what cause the density of localized states to vary spatially such as morphological dependence and dependence on grain sizes and shapes.

The long-term goal is to identify single charge carries pair recombination site and to measure spin-dynamics of single charge carrier pair. This understanding will help us to unravel the microscopic origin of spin-orbit interaction and how that varies spatially for a specific material or over a materials system. These understanding will help us to design better materials for solar energy harvesting.

Project-2. High-resolution magnetic field sensing using solid state spin sensors.

Efficient spin injection, spin accumulation, spin transfer and spin detection in correlated electron systems at nanoscale are key factors in utilizing the spin degree of freedom as a new functionality in spin electronic devices. For example, spin degree of freedom in magnetic nanoparticle (MNP) including molecular magnet has many uses such as data storage, magnetic memory, quantum information science, bio-sensing, medical imaging, drug delivery, and hyperthermia treatment. These applications would benefit from using MNPs with highly uniform spintronic properties such ferromagnetic resonance characteristics.

In this project, I am proposing for microscopic and spectroscopic investigation of magnetic properties in magnetic nanosystems *at variable temperature including room temperature*. The projected spatial resolution will be <*10 nm and magnetic field detectivity will be 10 $nT/\sqrt{Hz}$ spanning frequencies from near DC to gigahertz. The sensor in this measurement is nitrogen vacancy (NV^-) center in diamond, a remarkable sensor with ~nT/√Hz field detectivity [2] and 10 mK/√Hz temperature detectivity [3] - all in an atom-sized active element.*

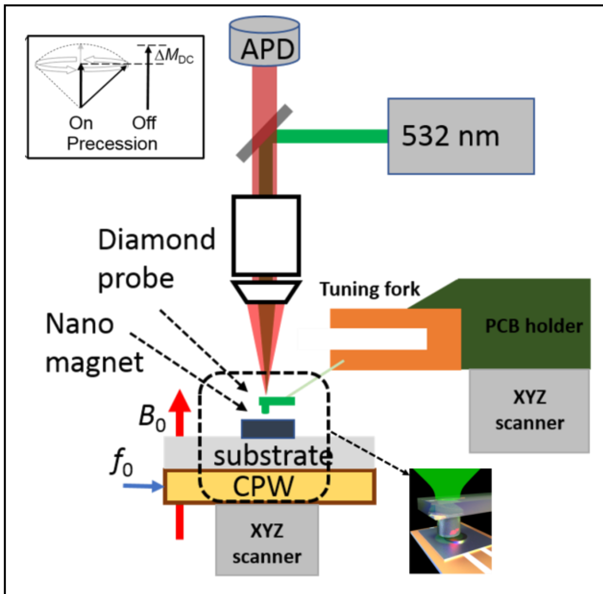

Fig.2 Scanning confocal magnetometry setup for nanoscale magnetometry using NV center. The stray magnetic field changes due to change in magnetization (ΔM_{dc}) (shown in box) will be used to measure magnetization dynamics of nanomagnet.

Proposed experimental method: A quartz tuning fork based scanning probe is at the heart of NV center magnetometry setup. Quartz tuning fork, with an electrical detection scheme, will enable optical access for the NV center. The NV center will be situated at the apex of the diamond probe [4] and photoluminescence (PL) from the NV center will be collected using objective as shown in fig.2. Using scanning probe, physical dimensions and structural defects of magnetic nano-devices will be measured. Change in magnetic field during ferromagnetic resonance (FMR) excitation of the nanodevice will be recorded by monitoring change in static magnetic field ($\approx\Delta M_{dc}$) as shown in fig.2. Using scanning static field imaging, spatially resolved static magnetic field image will be acquired during FMR excitation of magnetic nanosystems.

Goals: The short-term goal of this project is to develop deep understanding that what cause magnetic properties to vary among identical magnetic nano-devices. This goal will be achieved by various measurements; 1) measurement of magnetization dynamics (FMR, spin-damping rate) of nanoscale magnetic devices at room temperature, 2) measurement of magnetic exchange stiffness of ultra-thin (~1 nm) magnetic layer for magnetic memory applications, and 3) measurement of spin-noise from magnetic nano-structure using relaxometry of NV- center.

The long-term goal is to develop comprehensive understanding about various mechanism involve for efficient spin injection, spin accumulation and spin transfer in magnetic and non-magnetic materials. For examples, this project will yield comprehensive study of key mesoscale physical process that cause spin accumulation due to spin-Hall effect caused by spin-orbit scattering of conducting electrons in nonmagnetic materials and what cause the nonequilibrium spin accumulation at the interface of ferromagnet and non-magnetic materials such as normal metal and semiconductors during spin-polarized carriers' injection via ferromagnetic layer

In addition to correlated electron systems, the proposed scanning magnetometer would be a powerful resource for research in biophysics because it would enable the visualization of heterogeneous processes in biological systems including single-molecule spectroscopy and effects of local temperature on biological processes. Since biological research using scanning magnetometer is beyond my initial research plan, I will either pursue it in collaboration with an existing group working on biophysics or medical physics or focus on it after my lab is well set up.

Project-3. Electrically readout individual donor spins for quantum information science

Solid-sate spins, particularly spins of impurities in solids, are promising platform for realizing many quantum technologies such as quantum network, sensing and quantum information science because of their long coherence and compatibility with scalable device engineering. Among many quantum systems, spin states of a donor atom embedded in crystalline silicon are among those with the longest coherence time. In contrast to other semiconductor materials, silicon seems better for providing the perfect quantum solitude for spins because the spin of the silicon nucleus is zero (in enriched ^{28}Si) and there is comparatively weak spin-orbit coupling.

It is necessary to identify and address individual donor spin states to used them for quantum information science (QUBIT). Traditional way of measuring donor spin states is electron spin resonance via inductive detection scheme. But detecting individual donor spin states using traditional spin resonance experiment will require to measure microwave energy absorbed/ emitted by spin-polarized individual donor states. Therefore, detecting single donor spin states by traditional approach is extremely challenging.

However, electrically detected spin resonance has many advantageous as oppose to traditional spin resonance experiment. Electrical detection scheme uses the spin-selection rules i,e current change during magnetic resonance excitation depends on the probability of producing singlet charge carrier pairs over triplet of charge carriers pairs. So, magnetic resonance signal intensity is independent of spin-polarization. And it has been shown in past that single spin can be detected via electrically detected spin resonance technique [6-8].

In this project, I am proposing electrically detected single spin resonance of individual donor spin states via local amplification of spin-controlled currents. The proposed experiment will identify physical location of individual donor atoms and will readout the spin orientation of individual donor spin states.

Proposed experimental methods:

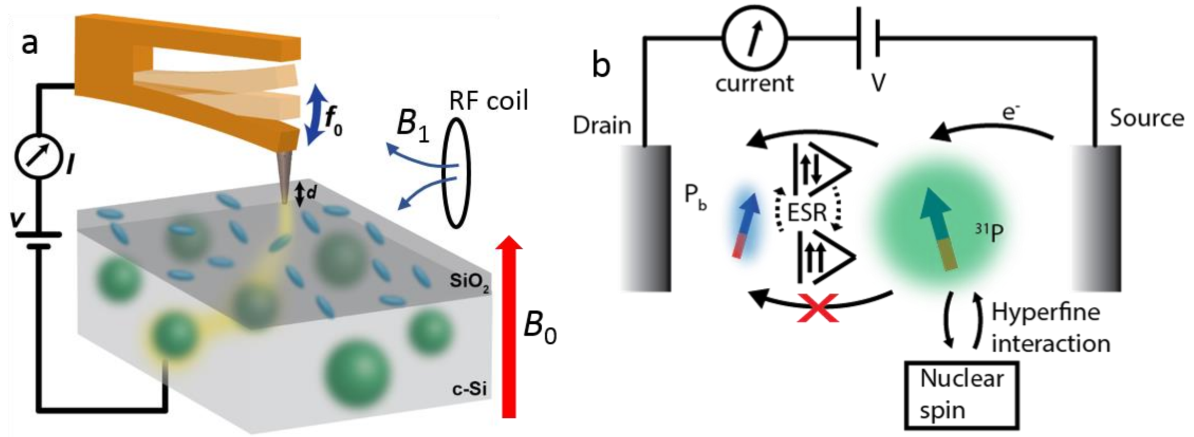

Fig.3: (a) Schematic of current imaging experiment on a phosphorus doped silicon substrate. A quartz tuning fork with a Pt tip attached oscillates at f_0. When a bias voltage V is applied to the probe, electrons tunnel from highly localized silicon dangling bond (blue ellipsoids) into the Pt tip. Due to high density of P dopants (indicated by green spheres), the substrate allows for percolation (path indicated by yellow halo) of charges through the bulk. (b) Schematic of spin dependent charge transport via donor atoms and silicon dangling bonds (P_b center) Single spin will be detected by measuring current change during magnetic resonance excitation.

The central equipment for this experiment is a quartz-tuning-fork-based, UHV, scanning probe microscope that works at low temperature with applied magnetic field. Using current map technique (conduction AFM technique) [9], single donor electronic state will be identified and current percolation through donor atoms will be measured as shown in fig.3. Magnetic resonance spectra will be recorded by monitoring the current change during magnetic resonance excitation at individual donor site.

Goals: The short-term goal of the proposed project is to identify individual donor electronic states and measure the spin states of individual donor atoms via hyperfine coupling between electron-spins and nuclear-spins as shown in fig-3b. In long run plan is to measure individual nuclear spin states of individual donor atoms. These measurements will help to standardize the process to write and read information to/from individual quantum bit (Qubit).

The long-term goal is to develop and use atomic scale lithography via scanning tunneling microscopy to implant single isolated donor atom with atomic precision and measure entanglement between nearest neighbor of donor atoms for quantum computer applications.

In addition to quantum information science research, the proposed nanoscale electrical spin measurement scheme would be a powerful resource to study localized states in many condensed matter systems including semiconductors and dielectrics. Particularly, localized states present in semiconductors and dielectrics are one of the key reason for inefficiency and device failure. Therefore, understanding these localized states will help to reduce their density and will help to build better devices.

Potential funding sources: In consideration of current funding environment, I will apply to diverse funding agencies, foundations and companies, particularly those that offer programs for new faculty. A few specific examples are listed below.

Agency	Program	Description
NSF	CAREER: Faculty early career development program	High resolution measurement technique of local carrier dynamics in thin film solar cells.
DOE	Early Career Research Program	Interface engineering for low cost, high-efficiency amorphous solar technology.
NIST	Measurement Science and Engineering (MSE) Research Grant Programs	Advanced measurement techniques for nanoscale magnetic media.
DARPA	Young Faculty Award (YFA)	Investigation of magnetization dynamics of nanoscale magnetic devices.

Student engagements in the projects

In my research group, there would be focused research plan for every graduate and undergraduate students based on their interest. Research plans will be designed such that there will be overlap between projects to promote collaboration among students. The projects will be designed such that during regular semesters (fall, spring) the undergraduate students will be able to make progress in their research "bit by bit" working in between classes. My group's research activities will engage students and encourage them to collaborate with others within and outside the research group. Regular, informal interactions in the laboratory, along with formal monitoring of research progress via research reports and group meetings will be the mainstays of my mentoring activities. Discussions about each student's goals will help me guide them in strategic planning and in directing them to appropriate professional development opportunities via research presentations at broad scientific gatherings like the American Physical Society, entrepreneurship workshops, or physics education meetings.

References:

[1] U. Dürig et. al., *J. Appl. Phys.* **59**, 3318 (1986).
[2] L M Pham et. al., *New Journal of Physics* **13**, 045021 (2011).
[3] Jean-Philippe Tetienne et. al., *Nano. Lett.* **16**, 326 (2016).
[4] P. Maletinsky et. al., *Nat. Nano.* **7**, 320 (2012).
[5] M. Pernpeintner, et. al., *arXiv*:1709.01820
[6] J. R. Pette, et. al., *Science* **309**, 2180 (2005)
[7] C. B. Simmons et al., *Phys. Rev. Lett.* **106**, 156804 (2011).
[8] M. Xiao et al., *Nature* **430**, 435 (2004).
[9] K. Ambal et at., *Sci. Rep.* **6**, 18531 (2016)