Research Statement

Background

The completion of my master's in Physics and Material Science initiated my professional life as a Physicist and Material Scientist. Subsequently, I worked as a senior project associate at Indian Institute of Technology, Kanpur, India which is an acclaimed and reputed research institute in India. The rigorous coursework and exposure to applied research projects taught me how to design experimental setups for multipurpose experiments. The deep understanding and hands-on experience involving material synthesis, structural, optical, electrical characterizations and multiple spectroscopic techniques led me to the United States to pursue a doctorate in Physics. With 15+ years of research experience, I am well acquainted with the AC/DC measurements and operated many experimental instruments like lasers, spectrometers, semiconductor analyzer, SEM, impedance analyzer, thermal/E-beam evaporation (Deposition), vacuum pumps etc.

My PhD dissertation "Optoelectronic Investigation of Single CdS Nanosheets and Single GaP/GaAs Nanowire Heterostructures" signifies the benefit of photocurrent spectroscopy to characterize the electronic band structure of semiconductor nanodevices. With my expertise, I have demonstrated the applications of cadmium sulfide-based nanomaterials for the applications of designing ultra-sensitive chemical and biosensor. I proposed the reliable, robust and low-cost photocurrent spectroscopy techniques to characterize and calculate the figure of merit of semiconductor nanomaterials. My research established the materials for energy bandgap engineering.

During my tenure as postdoctoral scholar at the Ohio State University, I used optoelectronics techniques that helped in revealing the degradation mechanisms of wide bandgap gallium nitride based high electron mobility transistors (HEMTs), which are used in space-shuttle applications and automobile industry. Additionally, these techniques also provide insight on defect levels within the energy bandgap introduced by high energy (proton) irradiation which is very important to improve the present state of the art applications of these transistors. As a senior project associate at IIT Kanpur, I have fabricated the thin films of high dielectric constant materials. This research is of high significant to the semiconductor industry to reduce the size and production cost of semiconductor devices for continuous improvements in semiconductors as predicted by Dr. Gordon Moore, the co-founder of Fairchild Semiconductor and Intel.

Currently, I am working on perovskite and self-assembled InAs/GaAs quantum dots (QDs). The use and applications of QDs are wide in range and thus are applicable in several areas such as quantum computing, solar cells, transistors, LEDs, medical imaging etc. I studied the perovskite QDs to understand the degradation mechanism and methods through which the stabilization of the materials can be attained for industrial implementation. In addition, the emission of light is realized through the vibration of the crystal membrane that are embedded in self-assembled InAs/GaAs quantum dots. The squeezing and stretching of the quantum dots ultimately results in the emission of light at frequencies shifted by an amount linked to the vibration of the membrane. This discovery has applications in quantum dot gravity gradiometer devices that measure minute changes in gravity and have direct applications to national security.

The importance of my research can be realized through the fact that it received international recognition. I have published about 10 peer-reviewed and proceeding articles in the leading journals in my field and presented work in leading conferences. In addition to this, there are a number of times that my work has been cited (more than 85 times) by researchers from all over the world. Not only this, my research is implemented by many research groups throughout the world and has been utilized in technology development in several areas. This demonstrate importance of my research to the science community, and civilization in general.

Future Research Plans

My plan is to continue working on semiconductor nanomaterial and quantum dots for the impact they have in research field and technology development. My research prospects include domains that will have applied applications in vast areas including technology development, national security and understanding the fundamental Physics concepts. My research aims at uncovering the huge potential that nanotechnology holds for world growth, national security and technology development.

There are several other projects that I want to work on in the future, each one of which is briefly discussed below:

1. **Photocurrent spectroscopy of chalcogenide semiconductors: a new generation of 2D materials.**

The exploration and characterization of new generation 2D material has improved with the passage and photocurrent spectroscopy can be important to the whole process. A material has been found, namely Graphene, that can be termed as "a rapidly rising star on the horizon of materials science and condensed-matter physics". An entire avenue of remarkable applications has opened up with the help of this heat and electricity conductor which has proven to be the lightest and the strongest. The lack of natural energy bandgap in graphene carries challenges for optoelectronics device application. The gap left by grapheme can be easily filled by using sizeable bandgap of transition metal chalcogenides (TMCs) as well as transition metal dichalcogenides (TMDs) semiconductor. These TMCs/TMDs semiconductors are the ones that will be used by me however, with different bandgap energies to form a heterojunction to tune the materials properties for different optoelectronics applications. The monolayers of bulk TMDs crystal will be exfoliated using the noble idea of mechanical exfoliation by a scotch tape. The other exfoliation techniques will be explored. There are several materials that will be used in this study, but the most notable ones include; MoS_2, $MoSe_2$, WS_2, WSe_2 etc. These are transparent and flexible with direct energy bandgap. The p-n junctions of these heterojunctions offer tunnel field-effect transistor (FET) for logic devices that run on very lower power. These materials will be used in high-performance electrical and optical devices including displays, sensors and complex integrated system. This research has potential in energy conversation and storage applications.

2. **Modeling of nanoparticle plasmonic resonator for nanodevice applications.**

Semiconductor nanostructures with and without plasmon enhancement are studied and explored extensively for nanodevice applications ranging from bio/chemical sensors to medical monitors and photovoltaics. The principle of biosensor development is to combine synergistically two powerful effects in semiconductor and metallic nanostructures, in order to create an extremely sensitive self-contained device for detecting pathogens. These are known as the sensitivity of strong localized surface plasmon resonances (LSPR) and the ability to flexibly tailor one-dimensional nanostructures and their properties to obtain highly nonlinear excitation of photocurrents. We imagine the case where a light beam illuminates a nanowire photodetector and does not create a photocurrent unless a pathogen becomes bound to nearby noble metal nanostructures. This ultimately leads to the creation of a strong photocurrent within the nanowire through the oscillation of plasmon to shift into resonance with the light beam. The absorption space as well as the photocurrent increases when nanoparticles are attached to nanowires which leads to the enhancement of the local electric field by orders of magnitude. Plasmonic resonances strongly depends on the size, shape, spacing and interaction of metal nanoparticles with semiconductor nanostructure. A lot of resources as well as efforts are required to realize plasmonic resonator devices and optimization with different shapes and sizes. In contrast, device modeling and simulations offer a much economical substitute to tackle such challenges.

To solve this problem in most economical and reliable mode, my proposition is to use Maxwell equation solver which helps in simulating the nanoparticles as surface plasmon resonator on the top of semiconductor nanostructures. The sharp features as well as the nanoparticle asymmetry is usually used for reported the enhancement of the electric field. To enhance the absorption rate as well as the photocurrent signal, I will simulate the electrical field profile for spherical, cylindrical, and bipyramidal nanoparticles (of different materials) and model the interaction of these nanoparticles with semiconductor nanostructures. After the achievement of enough absorption, my next step would be the stimulating of data which will be followed by the construction of a plan that outlines the best fabrication condition and parameters for highly sensitive photodetector and nanodevices.

3. Reliability testing of nitride semiconductors and devices

Nitride based devices, especially high electron mobility transistors (HEMTs) are adopted in a wide range of applications because of many advantages including high power and high frequency operation. However, reliability, especially in high radiation environments is still an open question. The performance of these materials and hence devices is hindered by the existence of electrically active defects that manifest as deep levels in the energy bandgap. The objective is to develop advanced thermal, electrical, optical, and imaging based trap spectroscopy techniques to directly probe and track traps in these materials and determine how they are connected to device performance. One example of determining the defect locations within the energy band is the DC and pulsed IV measurements, by comparing the current drops before and after stressing. The highly sensitive pulsed IV measurements could selectively detect the defects responsible for device degradation by measuring the IV at different times during the pulse. The principle of this measurement is the variation in the emission time constants of charge carriers trapped at different energy label within the wide band-gap. One could apply thermal, optical and electrical techniques to probe the complete energy bandgap. In addition, we could apply imaging techniques like scanning electron microscope and atomic force microscope to physically observe these defect states. Such techniques have significance to improve the material growth and hence device performances.

4. Investigation of spin-phonon coupling of coupled quantum dots and mechanical resonators for gravity gradiometer application

In this project, I rooted for the investigation of spin-mechanical interactions of quantum mechanical systems that are used in gravity gradiometer applications. This project is particularly important as it helps in improving the gravity-based detection of mass density distributions. There are a variety of applications for which gravity gradiometer including; resource exploration, navigation and defense operations and can be used to detect minute differences in the gravitational interaction between objects. An atomic interferometry-based quantum gravity gradiometer is even more sensitive (4×10^{-9} g/Hz$^{1/2}$) for high resolution mapping of mass distribution of interior of the Earth or other astronomical bodies. The objectives I have set for myself regarding the project include exploring the potential of quantum-controlled sensitivity of quantum dots optical transitions to detect and enhance the sensing of gravitationally induced motion via spin-phonon coupling. The study particularly revolves around enhancement of sensing the capability by favoring the quantum tunneling within two coupled quantum dots using structural engineering, electric, magnetic and optical fields and couple the quantum states to the phonon excitations. The realization of spin-phonon coupling based highly sensitive quantum-controlled gravity gradiometer system requires executions of highly spin-sensitive optical spectroscopy techniques, such as Ramsey-fringes and Raman spin-flip spectroscopy and boon to understand the fundamental physical constants.

These outlined research plans do not require expensive laboratory set up. All the purposed work could be accomplished with internal or external collaboration. To keep pace with outside world we may seek some collaboration within the university and neighboring universities and research labs. By such collaborations, students get opportunities to learn the research going around and get exposure of equipment's and research which cannot be offered within the department. In addition, I will publish the outcomes in high impact scientific journals. I believe that the best way to capture student interest and create enthusiasm for Physics is through research in close collaboration with faculty members.

The focus of my past research papers as well as the current ones have real-time application and use. The research conducted by me so far can be implemented in a variety of fields and is of significant benefit to the semiconductor industry, US defense, and military operations. This research has further inspired me to pursue similar goals in future studies. Hence, my aim is to continue adding value and worth to the existing scientific literature through which communities and people at large gain benefit. My work, so far, has been able to facilitate a large proportion of people and I am confident that it will continue to positively influence several fields.