IISc Quantum Technology Initiative (IQTI)

VISION DOCUMENT

iqti.iisc.ac.in | @IIScQuanTech | office.iqti@iisc.ac.in

IISc Quantum Technology Initiative (IQTI)

1. Background

Attempts to understand a variety of phenomena observed at the atomic scale led to the formulation of quantum physics in the early part of the twentieth century. That allowed us to understand how properties of bulk materials arise from their quantum origin, and subsequent harnessing of these properties produced technological applications, such as semiconductors, superconductors and lasers, in the second half of the twentieth century. These applications have made an enormous impact on society, and without them ubiquitous electronic gadgets, computers, mobile phones and internet would be unthinkable. Nowadays, this breakthrough is referred to as the first quantum revolution. It has been incessantly driven and sustained by miniaturization of the elementary device components. In the process, technological developments reached such a stage towards the end of twentieth century that it has become possible to control and manipulate individual quantum degrees of freedom. The paradigm shift from observation to control has opened a new door, and what we can achieve with such capabilities is dubbed the second quantum revolution. It aims to make novel quantum devices that would make essential use of quantum properties (such as superposition, entanglement, squeezing and tunneling of quantum states) in their function.

The building blocks of these quantum devices are fundamental physical objects---spins, atoms and photons, generically described as qubits. They can be put together in many different ways to construct sensors and measurement devices, communication systems, computers as well as some other unimagined future applications. The ongoing attempts worldwide, focused on construction of customized quantum systems and materials, are directed towards bringing transformative advances in science, economy and society. They envisage orders of magnitude enhancement in the precision of sensors and metrological instruments, strategies for secure communications that would herald the arrival of a quantum internet, quantum computers that can tackle computationally hard problems, and disruptive advances in imaging and energy manipulation techniques.

India did not invest sufficiently in the first quantum revolution and is dependent on other nations for the modern electronic gadgets. India also has been a late entrant in the race for the second quantum revolution. But the immense potential of quantum technologies to give rise to transformative applications has been recognized, and the Government of India announced the “National Mission on Quantum Technologies and Applications (NM-QTA)” in 2020. The mission aims to lay a solid foundation in the field of quantum technologies by supporting fundamental and translational research, leading to the invention of new products, services, and the creation of a skilled human resource. While NM-QTA desires to catapult India to the midst of the second quantum revolution, limitations in the existing expertise and facilities available in India pose significant constraints on its advancement.

The Indian Institute of Science aspires to deploy a dedicated effort to address these challenges, by establishing a framework to promote collaborations between physicists, material scientists, computer scientists and engineers. IISc, being the key institute instrumental in helping India develop past strategic missions (Indian nuclear technology and space technology programs were conceived and nurtured at IISc), has a multi-disciplinary research faculty with an interest in quantum science and technologies. Prior to the present interest in quantum technologies, IISc has played a pioneering role in the country, for efforts to become self-reliant in areas of Condensed Matter Physics, Nanoelectronics and Nanoscience. Recently, with funding support from the Ministry of Electronics and Information Technology, IISc has established a multi-disciplinary Center for Excellence in Quantum Technology, in collaboration with the Raman Research Institute (RRI) and the Centre for Development of Advanced Computing (C-DAC), to deliver quantum-enhanced technologies.

2. Vision

Worldwide, developments in quantum technology show the following trends: (a) Practical applications are expected to appear first in sensing and metrology (already happening), then in communications and simulations (on the verge of happening), then as feedback to foundations of quantum theory, and ultimately in quantum computing. The number of physical qubits in a quantum device is approximately doubling every year, which exceeds the Moore's law often used to characterize progress in traditional electronics. (b) Conventional classical technologies are simultaneously improving as well. They can compete with and counteract quantum technologies in hostile situations, where the latter would be highly fragile. The very principles that promise potentialities of quantum technologies in cooperative settings, also expose their limitations. Addressing both these aspects together is crucial.

In this context, IISc is launching its quantum technologies initiative, IQTI, to participate in and contribute to the national initiative and strategic demands, and to achieve technology readiness at par with international programs. It will leverage the Institute's research expertise in the area of quantum technologies, and at the same time, form a visionary research and development platform through national and international collaborations. We envisage this initiative not to be just academic science; it would actively engage with industry and strategic partners to create technology with economic benefits and social impact. IQTI would use the well-established academia-industry interface of IISc to establish a vibrant start-up culture and ecosystem, in order to convert the promises of fundamental research into entrepreneurial activities for product development.

The multi-disciplinary nature of the ongoing R&D in IISc fits seamlessly in the requirement of quantum technology development, from core hardware and back-end engineering support to algorithms for cryptography and machine learning. IISc intends to build on-field deployable systems for quantum-enhanced performance, as well as explore new fundamental and engineering routes for disruptive quantum applications.

The multifaceted collaborative efforts of IQTI will target the following areas:

1. Core quantum technology:

(a) Quantum computation

(b) Quantum communication

(c) Quantum sensing and metrology

2. Theoretical and modelling support:

(a) Quantum and quantum-inspired algorithms, Software simulators

(b) Quantum information theory and error correction

(c) Quantum cryptography and post-quantum cryptography

3. Peripheral technology development:

(a) Quantum materials: Discovery, modeling and design

(b) Quantum materials: Device technology

3. Objectives

The aim of IQTI is to enable the promise of quantum science and technology, by operating in sync with the global developments in this field. Although this is an open-ended expedition in many aspects, it requires clarity for short-term goals and a vision for long-term targets. Anticipating an inclusive, sustained and globally competitive growth, some of the short-term and long-term objectives of IQTI are the following:

<u>Short term aims: (0–3 years)</u>

1. Reliable and high-fidelity elementary quantum components (e.g. individual qubits, single-photon sources, single-photon detectors, NV-center magnetometers, waveguide interferometers).

2. 8-qubit quantum processor with superconducting transmon technology.

3. Software simulators to verify and validate noisy quantum devices.

4. Quantum-inspired algorithms that can be executed on existing computers and devices (e.g. randomized algorithms, recommendation systems, generative adversarial networks, amplitude amplification with wave dynamics, post-quantum cryptography).

5. Peripheral devices (electronics and nanotechnology) to interact with quantum components, incorporating efficient hybridization techniques.

6. Novel materials and architectures (e.g. layered devices).

7. On-field trials, reliability testing, packaging etc. of viable peripheral and quantum-enhanced components.

8. Infrastructure development for large scale semiconductor and device processing needed for quantum applications (e.g. back-end electronics, and photonics).

9. Introduction of MTech and PhD programs specializing in Quantum Technology.

Longer term aims: (4-6 years)

1. Improve the accuracy of all the short-term targets achieved.

2. Multi-qubit quantum processors based on transmons, optical and other platforms. Especially, scaling up of the number of qubits in the superconducting transmon processor.

3. Campus-wide quantum-secured communication network.

4. High precision sensors, measurement devices and transducers. They will include magnetometry at ~$fT/Hz^{1/2}$ resolution with NV-centers, nano-*g* inertial sensing with cold atoms and trapped ions, and so on.

5. Hardware simulation of few-body quantum systems (e.g. molecular chemistry and biology, physics models, material design).

6. Creation of new devices by integrating elementary components.

7. Quantum illumination and imaging (LiDAR) at lab scale.

Within each of these focus areas, IQTI will steer

1. Basic research at both experimental and theoretical levels.

2. Translational research in emerging technologies for the market.

3. A national and international quantum research network through visitors' program. That would also introduce dedicated adjunct faculty positions, named chair professorships, industry affiliated positions etc.

4. Directed research through strategic partnerships to address problems of national interest.

5. Establishment of facilities for quantum device fabrication, testing and characterization.

6. Training and capacity building for the next generation of scientists, engineers, technicians and technocrats.

7. Research collaborations, meetings and knowledge exchange with leading domestic and international institutions.

8. Industrial collaborations and entrepreneurship development.

4. Organizational Capacity

4a. Academic Strength and Research Interests of IISc

IISc's strength is the breadth of its existing technical expertise, and ability to adopt and rapidly develop new expertise covering a wide spectrum from basic sciences to engineering and technology.

Academic strength:

The on-going quantum technology centric activities in IISc can be broadly categorized as below:

1. Core quantum technology

- Quantum computation: Building and bench-marking multi-qubit processors with superconducting transmon qubits (*In progress through funding from Ministry of Electronics and Information Technology*).
- Quantum communication: Development of photonic technology components and their on-chip integration for quantum communication, with the aim to demonstrate prototype quantum network within the Institute (*In progress through funding from Ministry of Electronics and Information Technology*).
- Quantum sensing and metrology: Quantum-enhanced sensors of electric and magnetic fields using NV-centers in diamond, integrated photonics for quantum sensing and imaging applications, interferometric devices to assist inertial navigation.
- Quantum materials and devices: Development of platforms for new qubit architectures, quantum emitters in patterned layered materials, single photon detectors using van der Waals heterostructures and superconductors, quantum-enhanced fibre optic channels etc.

2. Theoretical and modelling support

- Quantum computing and communication algorithms.
- Quantum-inspired algorithms for data analysis and logistics problems.
- Emulation of quantum logic circuits and measurement, Simulators of noisy quantum devices.
- Quantum error correction, quantum cryptographic protocols.
- Post-quantum cryptography.
- Quantum reinforcement learning and machine learning.
- Modelling and prediction of quantum materials.

3. Peripheral technology development and engineering backup

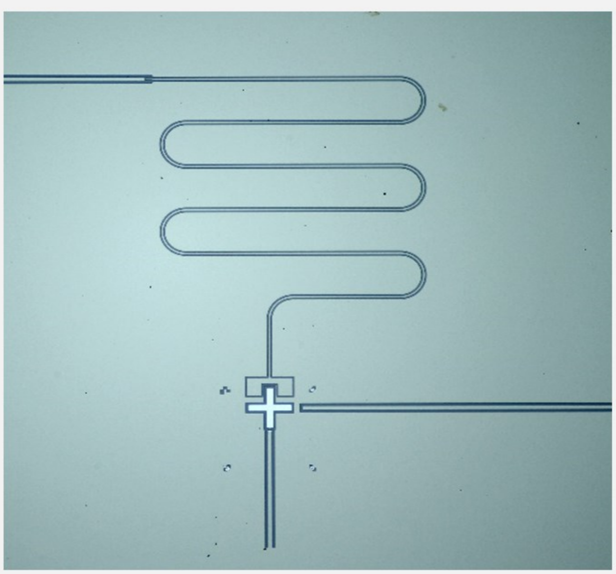
- Exploring and improving material synthesis and characterization for applications in all verticals of quantum technology.
- Device engineering, technology development and optimization to improve the coherence time and the gate fidelity of spin, photonic and transmon qubits.

- Microwave and radio frequency engineering design. Architectures for microwave antenna and radio frequency communications.
- Engineering of novel photonic architectures, coupled with emerging material synthesis, for high sensitivity ultra-fast optical sensing.
- Reliable technology for chip and system level integration of quantum components (packaging, thermal stability, EMI, variability control).
- Low temperature control electronics and measurement platforms.
- Heterogeneous integration of classical, neuromorphic and quantum technologies.

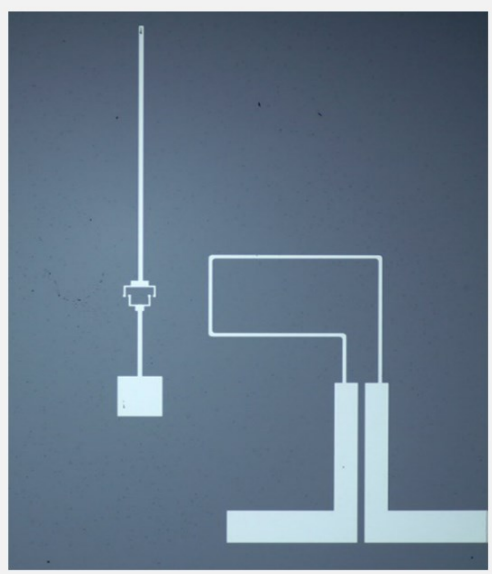
Research Interests:

A) Fundamental quantum technology

Superconducting transmon qubits: At present, the leading technology for building a quantum computer is based on transmon qubits in the circuit-QED architecture. Stable qubits with good control and coherence times have been demonstrated. Several groups around the world are constructing systems of 10 - 50 physical qubits. Challenge is the integration of individual components while keeping errors under control. With a basic set-up, single transmon qubits have been fabricated at IISc. We would like to expand this to multi-qubit systems, simultaneously developing packaging and DC/RF wiring configurations for cryogenic large-density architectures.
[Vibhor Singh (PH), Baladitya Suri (IAP), Chetan Singh Thakur (DESE)]



The primitive circuit-QED setup. An x-mon qubit (shown by plus-shape structure) coupled to a readout resonator (wiggly lines).



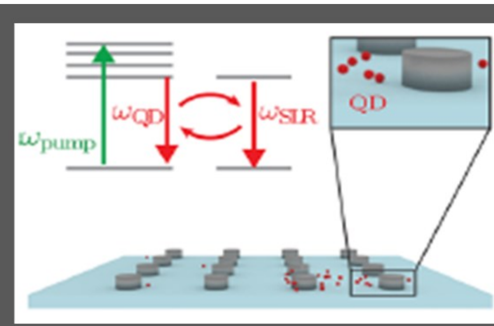
A transmon qubit designed for 3D cavity architecture with a fast-flux line.

Source: Dr. Vibhor Singh's group, Dept. of Physics, IISc

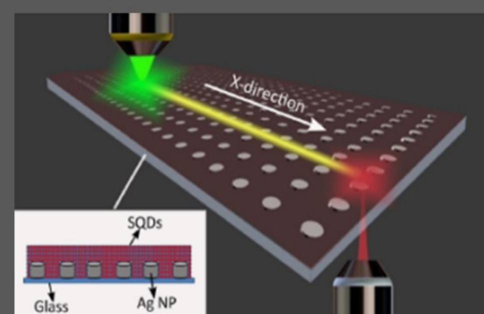
Photonic quantum processor:

Photons can carry quantum information in their polarization, space and time/phase degrees of freedom, and can be made to interact in nonlinear materials and waveguides. An on-chip photonic quantum platform operating at room temperature can be put together using emitters with controllable photon number and photon number resolving detectors. As identical particles, photons can demonstrate quantum supremacy in the boson sampling problem. They can be prepared in magic states, which are the starting point for distributed measurement-based computing and creation of multi-partite entanglement.

[Jaydeep Basu (PH), Shankar Kumar Selvaraja (CeNSE)]



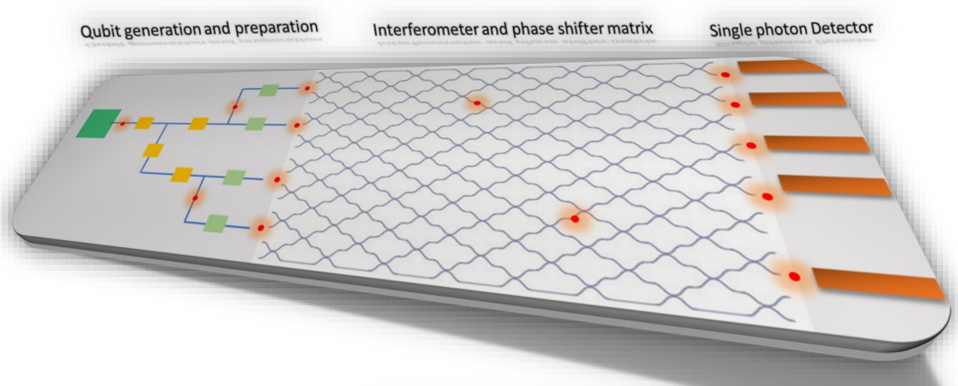
Scheme of coupling



Scheme for long range energy propagation

Source: Prof. Jaydeep Basu's group, Dept. of Physics, IISc

Single photon sources: Heralded photon sources, providing on-demand entangled photons, are crucial ingredients for quantum communications and quantum random number generation. Such photons have to be generated and filtered on-chip with high conversion efficiency, in telecom as well as optical frequency range. Point defects in layered materials and semiconductor heterostructures are being explored as promising nonlinear dielectric materials for this purpose.
[Shankar Kumar Selvaraja (CeNSE), Anshu Pandey (SSCU)]



Photonic Quantum Processor.
Source: Prof. Shankar Selvaraja's group, CeNSE, IISc

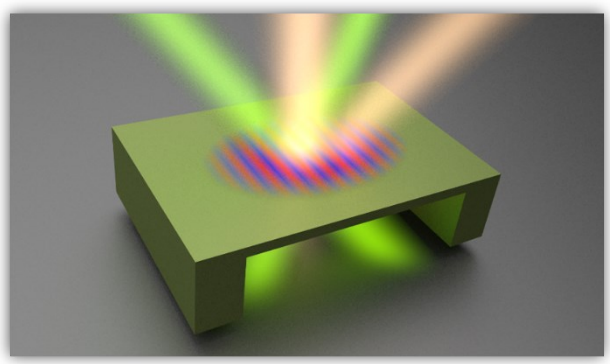
Single photon detectors: van der Waals hybrids of graphene and transition metal dichalcogenides are extremely responsive to optical excitations. They can be used to construct photon number resolving detectors, which are essential for quantum measurements and quantum communications. They can be part of precise nanoscale electromechanical sensors, ultra-fast bolometers and qubit readout schemes as well. The basic low temperature nanoelectronics facilities exist at IISc.
[Arindam Ghosh (PH), Kausik Majumdar (ECE)]

Quantum communications: Quantum sources and detectors need to be coupled to communication channels (either fiber based or free space) through necessary photonics and electronics. The components (waveguides, couplers, relays, ring resonators etc.) must preserve quantum coherence and match frequency during signal processing. Error correction protocols are essential to eliminate the noise that may enter during signal conversion between different components. A campus-wide low loss communication network with integrated photonic devices is being designed to demonstrate quantum key distribution and teleportation.
[Varun Raghunathan (ECE), Asha Bharadwaj (IAP), T. Srinivas (ECE), Shayan Srinivasa Garani (DESE)]

Colour defects in diamond: Nitrogen vacancy (NV) centers in diamond are highly sensitive and robust magnetometers. They can be hyperpolarized and integrated with motile colloids. When combined with well-established magnetic resonance imaging methods for electron spins, they can have wide-ranging applications---from industrial to medical ones. Silicon vacancy centres in diamond have high coherence and can help in forming quantum memories.
[Ambarish Ghosh (CeNSE)]

Quantum Sensing/Metrology:

Quantum metrology looks at ways to leverage the rules of quantum mechanics to improve measurement sensitivity, in order to detect tiny changes in physical observables. There is enormous interest in utilizing entanglement, squeezing and nonlinearities of quantum dynamics to improve measurement sensitivity significantly beyond what the classical systems permit. Sensitive qubits can be prepared and carefully positioned in two-dimensional transition metal chalcogenides and related semiconductors.



Schematic of transient grating.
Source: Dr. Navaneetha Ravichandran's group, ME Dept., IISc.

Measurement and characterization of their fundamental dynamics can improve photon signal sensitivity and thermometry by orders of magnitude.

[Akshay Singh (PH), Arindam Ghosh (PH), Kausik Majumdar (ECE)]

Hybrid quantum systems: Recent advances in quantum computing and measurements amply demonstrate the utility of tapping into hybrid systems that leverage the advantages of two of more types of systems. These systems would include coherent acoustic oscillators that interface qubits and communication systems, mechanical resonators that can function as quantum memory, electrons trapped in nanobubbles near liquid helium surface, and quantum sensors coupled to nanodevices.
[Vibhor Singh (PH), Akshay Naik (CeNSE), Ambarish Ghosh (CeNSE)]

Quantum devices using 2D materials: Layered 2D materials and heterostructures of 2D-3D materials offer a variety of possibilities to explore quantum devices. They span spin, charge and excitonic valley qubits, designs for transmon qubits and Josephson junctions, single photon emitters and detectors, and so on. Engineering challenges for large area fabrication, reliability, contact resistance, etc. need to be overcome.
[Arindam Ghosh (PH), Kausik Majumdar (ECE), Mayank Shrivastava (DESE)]

B) Theory, computation and software

Quantum algorithms: First generation quantum computers will be moderately sized and error-prone (not fault-tolerant). Demonstration of quantum supremacy with them requires finding suitable problems and solution strategies superior to their classical counterparts. Variational methods and universality properties of physical systems are useful ingredients in this search. Methods to verify the quantum results, without relying on classical cross-checks, are needed as well.
[Apoorva Patel (CHEP)]

Quantum simulations: First non-trivial applications of quantum computers are likely to be in direct simulations of models of quantum statistical mechanics, quantum field theory and molecular chemistry. Efficient techniques for these need to be developed, which have polynomial computational complexity with respect to both the input and the output number of bits.
[Apoorva Patel (CHEP), Rahul Pandit (PH)]

Quantum simulators: All quantum devices will be noisy and imperfect due to unavoidable environmental disturbances. They will need verification and validation of their performance. For systems of 10-20 qubits, the consequences of specific noises and imperfections can be estimated using their classical simulators, and that can help in improving the design and reliability of quantum devices.
[Apoorva Patel (CHEP)]

Quantum error correction and information theory: Error correction protocols are essential to eliminate the noise that may enter at any stage of quantum information processing. They are also needed to protect signal conversion between different components, to deal with occasional component failure, and to protect distributed quantum correlations over networks. Quantum information theory provides the framework to quantify capabilities of quantum channels and to design error correction codes. The fault-tolerant design strategy requires an error rate below a specific threshold and sufficient redundancy to guard against local disturbances. Graph-state analysis can provide efficient codes that safeguard multi-party entanglement and communications, against eavesdropping and node failure. Quantum algebraic codes over qubit/qudit states with entanglement-assistance can provide superior performance than without it.
[Shayan Srinivasa Garani (DESE), Navin Kashyap (ECE), Vinod Sharma (ECE)]

Open quantum systems: Identification of dominant environmental errors, and methods to suppress them, require careful modelling of quantum devices. The control and measurement components also bring in noise, and identification of decoherence-free subspaces that avoid noise is important. Models and algorithms need to be developed for noise-aware optimal control, fidelity estimation and error mitigation. Stochastic differential equations provide a useful framework, and the methods can mimic those followed in VLSI design and simulations.
[Soumyendu Raha (CDS), Soumitra K. Nandy (CDS)]

Post-quantum cryptography: Public key cryptographic systems, such as RSA, are vulnerable to quantum computers. New classical communication protocols that would be resistant to quantum attackers are being developed, such as lattice codes, multi-variate polynomials over finite fields and isogeny computation over elliptic curves. Rigorous cryptanalysis for quantum-safe key agreements and signatures is under investigation.
[Sanjit Chatterjee (CSA)]

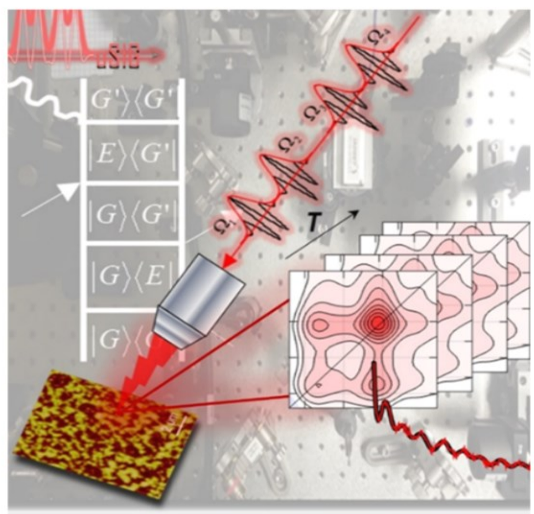
Quantum-inspired algorithms: Discoveries of efficient quantum algorithms have taught us to look at classical solutions to the same problems from a new perspective, leading to improved classical algorithms. Examples are randomized algorithms for optimization problems, spanning widely disparate areas such as recommendation systems, transport logistics and financial markets. These solutions have huge technological potential because they can be deployed with existing hardware. Yet another possibility is to exploit classical wave dynamics in amplitude amplification tasks, with applications to energy transfer and catalysis.
[Apoorva Patel (CHEP)]

Quantum-enhanced analysis methods: Machine-learning and artificial intelligence have become popular in problems analyzing immense quantities of data. They rely on clever combinations of multiple feature-identifying signals to identify the target objects. Quantum-enhanced methods would extend these to situations, where multiple signals do not merely add but can interfere constructively as well as destructively. Their applications can range from analysis of experimental data, images and communications to astrophysical and genome studies.
[Chiranjib Bhattacharyya (CSA), Apoorva Patel (CHEP), Sudhir Vempati (CHEP)]

C) Materials technology and engineering

The synthesis of materials, and the ability to precisely control and manipulate their properties, will play a major role in the next generation of quantum systems. IISc already has world-leading expertise in growth of 2D materials, heterostructures, oxides and other high-quality materials. This expertise will be leveraged to develop quantum materials with defect centres in ultra-pure materials, topological insulators, layered materials as well as heterogenous and designer materials. These quantum materials would be the precursors to developing a variety of quantum devices.

Discovery of new materials: Novel materials such as quantum defects with high spin-photon coupling, semiconductors with ultra-high thermal conductivity, heterostructures for quantum electronics and low-noise amplifiers, materials that suitably couple spin, phonon and electronic transport, are important targets. The Mott transitions in perovskite oxides, for example, can be used as trigger in new generation of high-performance bolometers for microwave and infra-red detection. Such materials need to be first designed with simulations, then synthesized and finally characterized by spectroscopy and electron microscopy, before incorporation in practical devices.
[Abhishek Singh (MRC), Navaneetha Ravichandran (ME), Pavan Nukala (CeNSE), Vivek Tiwari (SSCU), Srimanta Middey (PH)]



Femtosecond Multidimensional Spectroscopy can resolve the quantum coherent superpositions between qubits, and the coupling of qubits to a dissipative bath. Source: Prof. Vivek Tiwari's group, SSCU, IISc.

Topological materials: These can lead to noise-resistant quantum devices. Candidates being investigated are: Ferroelectric thin films that can accommodate skyrmions and vortices, materials simultaneously displaying spin Hall effect and superconductivity, frustrated spin liquids and Kitaev spin liquids that can possess Majorana excitations, and chiral Weyl materials.
[Pavan Nukala (CeNSE), Chandni U. (IAP), Srimanta Middey (PH), S.A. Shivashankar (CeNSE)]

Quantum thermodynamic systems: van der Waals heterostructures can be used to make quantum batteries and supercapacitors with small leakage, which are needed for high-speed electronics. MEMS/NEMS resonators can be designed to reach quantum limit of energy loss.
[Abha Misra (IAP), Saurabh Chandorkar (CeNSE)]

Optomechanical systems: In addition to electronic control, optomechanical systems have the advantage of being systems that can be easily coupled to different quantum systems including spins, photons and transmon qubits. In a large complex network of quantum systems, these mechanical or acoustic systems can play a major role as quantum memory, isolators, transducers and couplers of qubits and communication systems.
[Vibhor Singh (PH), Akshay Naik (CeNSE)]

Quantum memory: Electromagnetically induced transparency in optomechanical systems can be used to store information in mechanical modes of resonators. Multiferroic materials can be used for sensors and new types of memory.
[Akshay Naik (CeNSE), S.A. Shivashankar (CeNSE)]

Quantum system design: Many-body localization in disordered systems resists thermalization and decoherence. An understanding of their dephasing mechanisms can help improve the performance of quantum memory and sensors.
[Subroto Mukerjee (PH), Sumilan Banerjee (PH)]

Neuromorphic devices: Quantum computers will not be very efficient in solving several computational problems that can be easily addressed by von Neumann and neuromorphic architectures. They are therefore expected to be special purpose devices that would complement other forms of computing rather than replace them. So, it has been projected that future computing systems would consist of all the three forms, thereby requiring heterogeneous integration of qubits, bits and neurons. A technology platform that can cater to all the three forms of computing is needed. 2D materials offer one such platform, and IISc faculty has years of experience in developing devices and technology modules based on 2D devices.
[Chetan Singh Thakur (DESE), Arindam Ghosh (PH)]

Quantum dot based devices: Portable, power-free, cost-effective and eco-friendly devices can be made for detection and estimation of toxic elements in water. Nanoelectroactuation using graphene quantum dots can be used to guide stem cell functionality.
[Bikramjit Basu (MRC)]

Engineering and technological challenges: Overcoming these is going to be a key step that would translate science into practical technology. The efforts will include device design and engineering approaches to improve the coherence time and gate fidelity of various types of qubits, and efficient microwave engineering for creating multi-qubit entanglement while suppressing crosstalk.

Technology platforms for mK electronics and on-chip quantum control electronics: Control electronics in recently demonstrated quantum computers is forced to be far away from the qubits, because the superconducting transmon qubits operating at a few mK temperatures are kept inside a dilution refrigerator, whereas the control electronics is in a room temperature setup. This separation causes loss of gate fidelity, integration challenges, interferences and errors. A quantum computer designed for any practical purpose cannot afford such an operation. The problem can be addressed by bringing the control electronics next to the qubits, with a possibility to have the qubits and the control electronics on the same chip. That needs development of a technology platform for ultra-low temperature electronics.

System integration: To ensure reliable integration of components at the chip and system level, expertise is required in chip packaging, thermal design and management, electromagnetic shielding, as well as control over device and process variability.

4b. Existing Facilities & Infrastructure

National Nanofabrication Centre (NnfC):

The National Nanofabrication Centre has a 14,000 ft^2 clean-room facility with capability for:

- Photolithography with resolution of 1 µm for optical and 10 nm for e-beam lithography.
- Developing unit processes for chemical & physical vapour deposition (CVD) of most commonly used semiconductors and dielectrics, such as Si, SiGe, Ge, SiO_2, SiNx, Al_2O_3, TiO_2, etc.
- Developing unit processes for wet and dry etching of most commonly used semiconductors and dielectrics.
- Fabricating complete MEMS sensors, gas sensors, GaN HEMTs, Si solar cells, novel 1D and 2D devices including graphene and MoS_2, and photonic circuits.

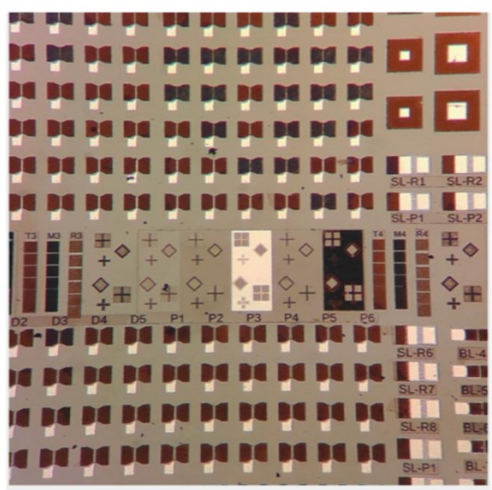
- Developing new and customized processes for MEMS/NEMS devices, microfluidic structures, and semiconductor devices for industries and other laboratories.
- A new ultra-high vacuum sputtering unit and a reactive ion etching unit for quantum devices.
- Inline characterization using various metrology tools.

National Nanofabrication Center at CeNSE, IISc

Micro and Nano Characterization Facility (MNCF):

The one of its kind micro and nano characterization facility (MNCF) aims to be a one stop solution for all characterization needs of any nanofabrication process. It is rare to find such a comprehensive array of tools under a single roof, anywhere in the world. Capabilities include:

- Complete electrical characterization of devices from DC to 110 Mhz, and at 4K to 400K temperature, using an array of probe stations and parameter analysers.
- Ability to characterize RF devices upto 70 GHz.
- Ability to measure power conversion efficiency and external quantum efficiency (EQE) of solar cells.
- Metrology of thin films using optical profilometer, acoustic microscopy and atomic force microscope (AFM), including advanced modes such as piezo response, conductive, magnetic-force, scanning-tunnelling atomic force microscopy, etc.



GaN FET developed by Prof. Mayank Shrivastava's group (DESE, IISc)

- Comprehensive characterization of bulk materials and thin films using Raman spectrometry, photoluminescence (PL), electroluminescence (EL), Fourier transform infrared spectrometry (FTIR), X-ray diffraction (XRD), X-ray reflection (XRR), photoemission spectrometry (UPS and XPS), and UV-Visible spectrometery.
- Field emission scanning electron microscopy (FESEM) with dual beam focused ion-beam (FIB), EDS and monochrometer (MonoCL), TEM.

Other facilities (distributed across different groups):

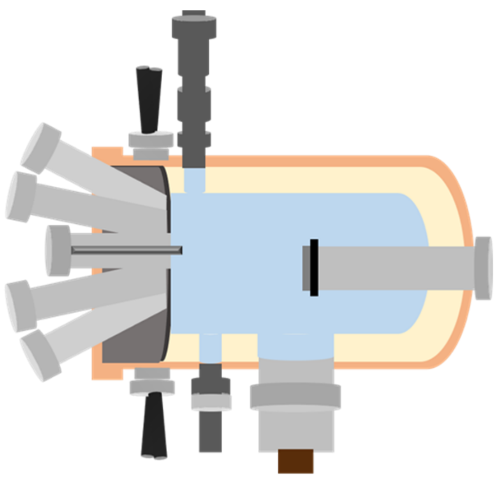
- Low temperature (4K) confocal Raman/PL setup for measurements with different excitation wavelengths (2 Nos: one with DC ports, and one with DC and RF ports).
- Low temperature (7K) electrical probe station for electrical/optoelectronic measurement of devices.
- Single photon level detection and correlation system consisting of timing electronics and single photon detectors.
- CCD camera having single photon detection capability.
- Low temperature (4K) confocal pulse (few 100 ns) Raman/PL setup with different excitation wavelengths.
- Set- up for thermal mapping with 50 ns time resolution and 500 nm spatial resolution. It can be mounted over any probe station as well as over an ultra-low vibration CC-LHe cryostat (in the same lab).
- Deep-level transient spectroscopy (DLTS) set-up to study deep level defects in quantum materials.
- Fully automated RF (0–70 GHz) probe station.
- Semi-automated L-N2 probe station with RF (up to 4 GHz) capability.
- Room temperature STM, SCM, CFM, SSRM, SThM & KpFM.
- Lock-in amplifier based set-ups for 1/f noise and thermal characterizations.
- Glove-box based set-up for 2D material device engineering (having integrated thermal evaporator, stamping stage with high resolution microscope and another dark field microscope with high magnification.
- Dilution fridge 10 mK with suitable microwave cabling, and related RF electronics such as Vector Network Analysers, signal generators, Arbitrary Waveform Generators, Digitiser, Scope.

- Another station for superconducting qubit (up to six) characterization and measurement is expected to be ready by April 2021.

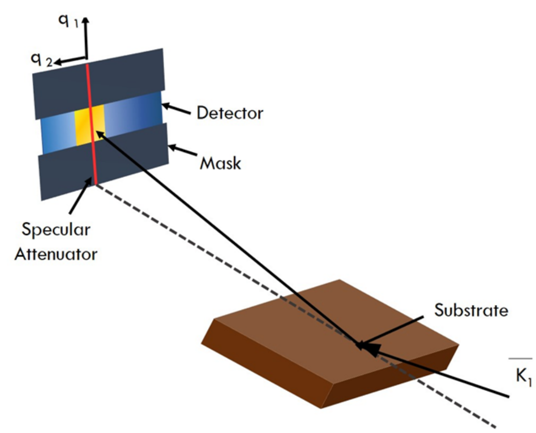
- Low temperature (15 mK) dilution refrigerator system for electrical and thermal transport and noise measurements in field effect devices, single crystals and thin films.

- Variable temperature optoelectronic measurement set-up for single photons in magnetic field.

- Material and device engineering set-up with 2D materials for studying novel superconductors, structural and topological phases, which may be useful in quantum communications as well as novel qubit platforms.



Deposition system for thin film and heterostructures of quantum materials



Schematic of Synchrotron X ray diffraction

Source: Prof. Srimanta Middey's group, Dept. of Physics, IISc.

5. Team

5a. Investigators

Name	Profile
 Apoorva Patel	**Apoorva D. Patel** is a Professor at the Centre for High Energy Physics, IISc. He is notable for his work on quantum algorithms, and the application of information theory concepts to understand the structure of genetic languages. His major field of work has been the theory of quantum chromodynamics, where he has used lattice gauge theory techniques to investigate spectral properties, phase transitions, and matrix elements.
 Arindam Ghosh	**Arindam Ghosh** is an experimental condensed matter physicist and a Professor in the Department of Physics, IISc. His research group is involved in investigating structural, electrical and magnetic properties of various nanoscale systems. His research interests extend from fundamental quantum mechanical effects on charge and spin states in nanosystems, to carbon-based electronics, critical behavior in smart materials, to new schemes of sensing with nano/micro-electromechanical sensors.
 Abha Misra	**Abha Misra** is an Associate Professor at the Department of Instrumentation and Applied Physics. Her group works on various aspects of nano and micro systems to study interfaces between different physical phenomena at nanoscale. Multidimensional carbon lattices including graphene, carbon nanotubes and quantum dots are being investigated for optoelectronic, gas sensing, self-powered as well as actuation devices at large scale. The device design paradigm is established through bio mimicking of natural systems for self-sustained network where two-dimensional van der Waals interfaces are largely utilized for spontaneous conduction mechanism.

Abhishek Singh

Abhishek Singh is an Associate Professor at the Material Research Centre, IISc. His research interests include quantum ab-initio theory for real materials, machine learning and material database generation, hydrogen generation and storage, mechanical, structural, electronic, and magnetic properties of nanostructures, theory of defects, impurities, doping and diffusion in bulk and reduced dimensional systems, thermal and electrical transport and quasiparticle and optical excitations. His group has found several ultra-low and ultra-high lattice thermal conductivity materials and developed a ML model to predict thermal conductivity of a large class of materials using physics driven four parameters.

Akshay Naik

Akshay Naik is an Associate Professor at the Centre for Nanoscience and Engineering, IISc. He conducts research in the areas of nano electromechanical systems, nonlinear dynamics, MEMS and NEMS sensors, and quantum measurements. His group has demonstrated the use of mechanical nanoresonator to enhance or reduce the energy exchange between the vibrational modes and the suitability of metallic carbon nanotubes (CNTs) as thermo-optic tuners.

Akshay Singh

Akshay Singh is an Assistant Professor in the Department of Physics, IISc. His lab uses a variety of optical and electron spectroscopy tools to characterize synthesized and naturally occurring materials. The group focuses on the measurement of fundamental dynamics, to discover new physical phenomena, and synthesize non-naturally occurring materials leading to advances in opto-electronics and quantum computing.

Ambarish Ghosh

Ambarish Ghosh is a Professor at the Centre for Nanoscience and Engineering, IISc. He is known for his contributions on nanorobots, active matter physics, plasmonics, and metamaterials. His group has wide interests in studying light-matter interactions in novel nanoscale systems, ranging from electron bubbles in superfluid helium to helical nanoplasmonic devices, and magnetic nano-propellers.

Anshu Pandey

Anshu Pandey is an Associate Professor at the Solid State and Structural Chemistry Unit, IISc. His research is aimed at understanding new physical properties that emerge in nanoscale matter. His group recently demonstrated ground state charge transfer between semiconductor nanocrystals, leading to the formation of "compounds" where individual quantum dots take the place of atoms. Yet other efforts in his lab are devoted to the development of semiconductors composed of earth abundant non-toxic elements, novel methods of synthesis and building materials with unusual properties.

Asha Bharadwaj

Asha Bharadwaj is an Assistant Professor at the Department of Instrumentation and Applied Physics. The main focus of her research group is on fabrication of high quality quantum dots. At present her group is working on colloidal carbon quantum dots and Transition metal dichalcogenide (TMDC) Quantum dots. Some part of her work is also dedicated to optimization of Quantum dots precipitation in a glass host.

Baladitya Suri

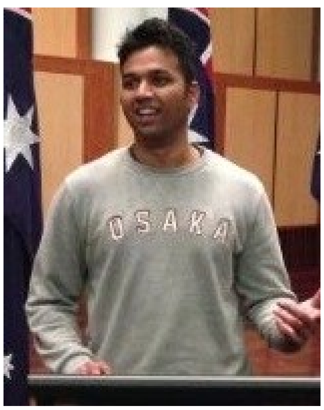
Baladitya Suri is an Assistant Professor at the Department of Instrumentation and Applied Physics. His group is interested in quantum information and quantum computation with superconducting circuits in particular, and solid-state circuits in general. His current work also involves coupling superconducting artificial atoms to propagating phonons on the surface of a piezoelectric substrate to realise the acoustic analogue of quantum optics— quantum acoustics. Another area of interest is that of single photon generators and detectors in the microwave regime.

Bikramjit Basu

Bikramjit Basu is a Professor at the Material Research Centre, IISc. His research group has effectively applied the principles and tools of these disciplines to develop the next generation implants and bioengineering solutions to address unmet clinical needs for musculoskeletal, dental, and neurosurgical applications. Encompassing experimental discovery, theoretical predictions, computational analysis, and clinical translational research, his research group has laid the foundation for biomechanically-compliant design of implants, 3D binderjet printing of biomaterials, science of biocompatibility and bioengineering strategies, to advance the field of biomaterials science and regenerative engineering; thereby impacting human healthcare.

Chandni Usha

Chandni Usha is an Assistant Professor at the Department of Instrumentation and Applied Physics. Her group studies electron transport in a variety of low dimensional semiconductor and metallic systems and in particular, two-dimensional electron systems in graphene and other layered materials, van der Waals heterostructures and ultrathin metallic wires. Other research interests include piezotronics and sensing using two dimensional materials and heterostructures.



Chetan Singh Thakur

Chetan Singh Thakur is an Assistant Professor in the Department of Electronic Systems Engineering, IISc. His research expertise lies in neuromorphic computing, mixed-signal VLSI systems, computational neuroscience, probabilistic signal processing, and machine learning. His research interest is to understand the signal processing aspects of the brain and apply those to build novel intelligent systems.

Chiranjib Bhattacharyya

Chiranjib Bhattacharyya is a Professor at the Department of Computer Science and Automation, IISc. His research interests are in foundations of Machine Learning, Optimisation and their applications to Industrial problems. His group actively pursues applications in the area of computational biology, object detection in images, video segmentation and summarization, detection of rare topics in text documents, and statistical modeling of computer systems.

Himanshu Tyagi

Himanshu Tyagi is an Assistant Professor at the Department of Electrical Communication Engineering and an Associate Faculty at the Robert Bosch Center for Cyber Physical Systems. He conducts research in the areas of information theory, statistics, cryptography, machine learning, distributed intelligence systems, and socio-technical systems.

Jaydeep K. Basu

Jaydeep K Basu is a Professor in the Department of Physics, IISc. His research interests include soft condensed matter physics, physics of biological systems, nanophotonics, quantum plasmonics, topological photonics. His group has developed considerable expertise in fabrication of single photon emitting quantum emitters as well as their arrays which can be readily coupled to optical and metamaterial templates. His group's work in the area of light-matter interactions at the nanoscale is well recognized.

Kausik Majumdar

Kausik Majumdar is an Associate Professor at the Department of Electrical Communication Engineering. His research group uses a combination of theoretical and experimental techniques to investigate the electrical and optoelectronic properties of low dimensional materials and their nanostructures. They also explore the possibilities of applying these properties to develop novel devices, encompassing the entire spectrum of device design and simulation, device fabrication using state of the art semiconductor fabrication techniques, and device characterization using various electrical, optical and spectroscopic techniques.

Manish Jain

Manish Jain is an Associate Professor in the Department of Physics, IISc. His research focuses on theoretical investigations of structural, electronic, and optical properties of materials from first principles using density functional theory and many-body perturbation theory, application of these methods to calculate experimentally observable properties of defects in solids and the development of new methods to calculate material properties.

Mayank Shrivastava

Mayank Shrivastava is an Associate Professor in the Department of Electronic Systems Engineering, IISc. His group works on the science and technology of electron devices, having focus on power semiconductor devices as well as nanoscale / beyond Si CMOS for SoC applications. Given a strong focus on the semiconductor technology for the future electronics, the group also work on a multitude of science threads like (i) physics of semiconductor device reliability, (ii) electro-thermal / electron – phonon interaction in beyond Si materials / devices, (iii) thermometry and thermal / phonon transport in these materials / devices.

Nandy S K

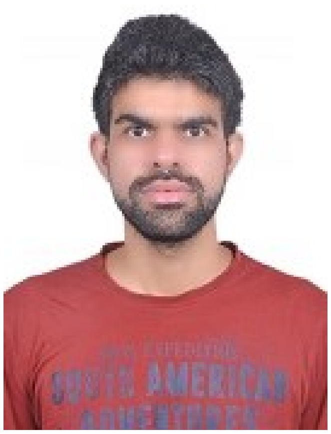
Nandy S K is a professor in the Department of Computational and Data Sciences, IISc. His conducts research in the areas of application specific instruction set processor architecture, reconfigurable high performance processor architectures, systems on silicon, compiling techniques for low power, architectural synthesis of high performance VLSI systems, parallel/pipelined low latency, high throughput arithmetic unit architectures, multi-threaded architecture and global shared memory cache coherence protocols.

Navaneeth Ravichandran is an Assistant Professor in the Mechanical Engineering Department, IISc. He is interested in studying the electronic and thermal properties of semiconductors and metals. Specifically, his group focuses on developing computational and experimental tools to probe the microscopic, quantum-mechanical interactions among energy carriers that drive these macroscopic properties.

Navaneeth Ravichandran

Navin Kashyap is a Professor in the Department of Electronics Communication Engineering. His research interests include Coding for Data Communication and Storage, Information-Theoretic Security, Source Coding, Data Compression, Data Synchronization, Symbolic Dynamics and Discrete Applied Mathematics.

Navin Kashyap



Pavan Nukala is an Assistant Professor at the Centre for Nanoscience and Engineering, IISc. His research interests are in correlated systems, ferroelectric and multiferroic thin films, topological defects and functions in context of quantum computation, *in situ* electron microscopy and spectroscopy, material networks for neuromorphic computing, phase change materials and thin film X-ray diffraction.

Pavan Nukala

Rahul Pandit

Rahul Pandit is a condensed matter physicist and a Professor in the Department of Physics, IISc. His research interests include problems in condensed-matter theory, phase transitions, statistical mechanics and nonlinear dynamics. He is known for his research on phase transitions and spatiotemporal chaos and turbulence.

N. Ravishankar

N. Ravishankar is a professor at the Materials Research Centre, IISc. He is known for his studies on nanostructured materials and the primary research in his lab focuses on wet-chemical synthesis, characterization and assembly of functional inorganic nanostructures for a variety of applications.

Sanjit Chatterjee

Sanjit Chatterjee is an Associate Professor in the Department of Computer Science and Automation, IISc. He works primarily in applied cryptography and information security with a special emphasis on practice-oriented provable security. Fascinated by the interplay of functionality, security and efficiency of cryptographic protocols, he conducts research in public key cryptography, identity-based cryptography, security protocols for cloud, pairing-based cryptography and quantum safe cryptography.

Saurabh Chandorkar

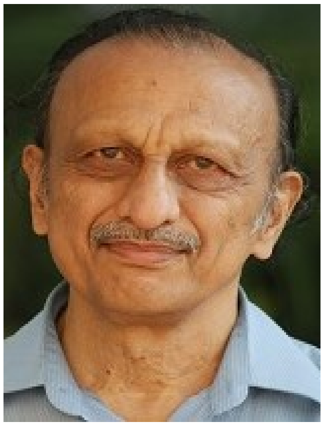
Saurabh Chandorkar is an Assistant Professor at the Centre for Nanoscience and Engineering, IISc. His research interests include energy loss mechanisms in micro/nano scaled resonators, wafer scale packaging for MEMS, human-computer modality enhancements and low-cost system development for IC fabrication and characterization.

Shankar K. Selvaraja

Shankar K Selvaraja is an Associate Professor at the Centre for Nanoscience and Engineering, IISc. His research area spans widely from material development to complex photonic device and integrated circuits. His group focuses on developing integrated photonics technology on a variety of substrates for data communication, signal processing and sensor applications.

Shayan Srinivasa Garani

Shayan Srinivasa Garani is an Associate Professor in the Department of Electronic Systems Engineering, IISc. His research contributions in the field of quantum science and technology are in quantum error correction, quantum coded networks and fault-tolerant quantum computing, linking physics and electrical sciences. The research emphasis is on solid mathematical foundations and algorithms leading to system-level architectures for harnessing entanglement towards a broad range of quantum information processing applications.



S. A. Shivashankar

S. A. Shivashankar is a Professor at the Material Research Centre, IISc. He conducts research in development of chemical precursors, MOCVD of oxide thin films, ALD of metals and metal oxides, thermodynamic modelling of the CVD process, microstructure development in MOCVD-grown films and properties of thin films. He is a lead investigator on the Indian Nanoelectronics Users Programme (INUP), a mission that makes the device fabrication and characterization facilities at IISc to researchers in various organizations throughout India.

Subroto Mukerjee

Subroto Mukerjee is an Associate Professor in the Department of Physics, IISc. His research interests include transport in strongly correlated systems, thermalization and many-body localization in quantum systems, physics of correlated cold atoms and statics and dynamics of lower dimensional quantum systems.

Sudhir Vempati

Sudhir Vempati is an Associate Professor at the Centre for High Energy Physics, IISc. He conducts research in the field " Physics Beyond the Standard Model " of Elementary Particle Physics. His group tries to build extensions of the standard model which can accommodate solutions to problems like hierarchy problem, non-zero neutrino masses, dark matter, baryogenesis, leptogenesis, cosmological constant or dark energy, flavour mixing etc. The frameworks they work are mostly supersymmetry, supergravity, extra dimensions and Grand Unified theories. In addition to model building, he is also interested in the theoretical aspects of these framework like Renormalisation group properties.

Sumilan Banerjee

Sumilan Banerjee is a theoretical condensed matter physicist and an Assistant Professor in the Department of Physics, IISc. The broad interest of his research group is to study the novel properties of strongly correlated quantum systems and to understand the interplay of interaction and disorder in many-body quantum dynamics.

Supradeepa V R

Supradeepa V R is an Associate Professor at the Centre for Nanoscience and Engineering, IISc. His research interests include High Power Fiber Lasers, Nonlinear Optical Frequency Conversion, Integrated Photonics, Optical Frequency Combs and Metrology and High Bandwidth Optical Communications.

Sushobhan Avasthi

Sushobhan Avasthi is an Associate Professor at the Centre for Nanoscience and Engineering, IISc. His research interests include high-efficiency perovskite thin-film solar cells, integration of semiconducting oxides to silicon, forming oxide/silicon heterojunction devices, functional oxide devices for applications such as photovoltaics, sensing, and memory, and integration of solar cell on novel substrates such as steel. His lab focuses on the design, fabrication and characterization of electronic devices. They are specialized in integrating different materials, e.g. silicon with metal-oxides and germanium with silicon and interested in studying the new functionalities and improved performance that such heterogenous integration may introduce.

Srimanta Middey

Srimanta Middey is an Assistant Professor in the Department of Physics, IISc. His research interests include emergent phenomena in oxide heterostructures, strongly correlated systems, metal-insulator transitions, superconductivity, magnetism, X-ray spectroscopy and scattering. His group explores various exotic electronic and magnetic phenomena such as superconductivity, metal-insulator transition, high mobility electron gas, spin liquid phase, and non-trivial spin texture.

T. Srinivas

Srinivas Talabattula is an Associate Professor in the Department of Electronics Communication Engineering. His research interest spans photonics integrated circuits, both theoretical and experimental, with application to optical communications and optical sensors. He is also interested in optical biosensors and quantum photonics.

Soumyendu Raha

Soumyendu Raha is a Professor in the Department of Computational and Data Sciences, IISc. His research interests include simulation, control and optimization of constrained dynamical systems, stochastic and deterministic differential-algebraic equation systems, mathematical libraries, and VLSI CAD applications.

Varun Raghunathan

Varun Raghunathan is an Assistant Professor in the Department of Electrical communication Engineering. His research interest lies in experimental photonics with a major focus on non-linear optics, integrated optic, flat land photonic components, and optical microscopy. His research group works on the design, fabrication and experimental characterization of micro-/ nano-fabricated photonic devices.

Vibhor Singh

Vibhor Singh is an Assistant Professor in the Department of Physics, IISc. The focus of his research is on superconducting devices based emerging quantum technology. Research in his lab spans a variety of activities such as cavity-opto-mechanics in microwave domain, superconducting materials for quantum devices, circuit-QED systems, superconducting qubit-based hybrid optomechanical systems.

Vinod Sharma

Vinod Sharma is a Professor in the Department of Electronics Communication Engineering. His research interests are in the areas of Communication and Computer Networks, Wireless Communication, Sensor Networks, Queueing Theory, Information Theory and Statistical Estimation Theory.

Vivek Tiwari

Vivek Tiwari is an Assistant Professor at the Solid State and Structural Chemistry Unit, IISc. His group develops spectroscopic techniques and quantum dynamical models to understand ultrafast energy and charge delocalization on the nanoscale. Projects in his lab involve both experimental and theoretical components.

5b. Programme Coordinators

Srividya Kumar

Srividya Kumar is currently working as Technology Manager for IQTI. Prior to this role, she has worked as Grants Manager at the Office of Research Grants, IISc. She did her B. Tech in Bioengineering at SASTRA University, Thanjavur. In 2018, she completed her doctoral research training in Biospectroscopy from Inorganic & Physical Chemistry Department, IISc.