Welcome to the Department of Condensed Matter Physics and Materials Science (CMPMS) at TIFR! Research in CMPMS asks questions about the nature of materials that are in the “condensed state” – familiar condensed phases like solids or liquids, but also more exotic phases such as the superconducting phase at low temperatures, magnetically-ordered phases etc. We also work on semiconductors and nanostructured materials, and soft-matter. We study the electronic, physical, mechanical, optical, and chemical properties of materials, in relation to their structure. Our emphasis is on the experimental measurement of various properties using different probes in an attempt to understand the underlying physical behaviour. We fabricate optoelectronic, plasmonic, and superconducting device structures that serve as test systems to study novel phenomena and also enable real world applications.

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**Research areas**

A common question across various research groups is how electrons organize themselves in different materials giving rise to a host of interesting physical phenomena. Strongly correlated electrons are responsible for many phenomena in solid-state physics, especially in the areas of magnetism and superconductivity, and physics at ultra-low temperatures. In semiconductors, confining electrons to very tiny nanometer-sized regions in thin sheets, narrow wires, or small boxes results in quantum wells, wires and dots, where their properties are modified by quantum mechanical effects in dramatic and potentially useful ways. The interaction between an electromagnetic field and free electrons in a metal can result in coherent electron oscillations at the interface – “plasmonics” tries to study and make use of these oscillations by patterning materials at the nanoscale. Superconductors can be used to build electrical circuits engineered to behave like quantum two level systems for applications in quantum computing.

On the materials science side, we study the electronic, physical, mechanical, optical, and chemical properties of materials, most often in relation to their structure, and use this knowledge to understand and optimize their properties and create new, improved materials and devices. Increasingly, the functionality of modern materials depends on control of their structure at the atomic scale. “Soft” condensed matter research explores areas like adhesion, friction, wetting, and the movement of fluids in porous media etc.

**Experimental facilities**

From exploring basic materials properties to the fabrication of advanced electronic, nano-mechanical, and optoelectronic devices, the experimental facilities in CMPMS are comparable to the best world-wide. These include materials synthesis facilities like single-crystal growth, epitaxial deposition of semiconductors, chemical vapour deposition of graphene, pulsed laser deposition, sputtering and other thin-film growth techniques. Characterization tools range from optical spectroscopies such as photoluminescence and Raman scattering to ultrafast time-resolved pump-probe measurements with samples being probed from the UV through the visible/IR and into the THz region.

Structural properties are determined using high-resolution x-ray diffraction, ultra-high-resolution electron microscopy, scanning tunneling microscopy and other scanning probe techniques. For measurements of the electronic and magnetic properties SQUID and other sensitive magnetometers, high-resolution and spin-resolved photoemission spectroscopy, and precision transport studies at ultra-low temperatures, in individual nanostructures and up to the GHz frequency range are available. The soft-condensed matter lab has setups for imaging complex fluid flows. We also have a small but well-equipped clean room for micro and nano-fabrication including optical and electron-beam lithography, plasma etching, thermal and electron-beam deposition, atomic layer deposition, etc.

**A world of opportunities**

From superconductors and magnetic materials, to semiconductors and nanostructured metals, research in CMPMS covers a diverse range of “matter that matters” in today’s world. The diversity of systems and phenomena available for study makes condensed matter physics the most active field of contemporary physics today. Not surprisingly, it is also the area of physics with the widest choice of job prospects, and our graduate students have gone on to exciting careers in academia and industry across the world.

The following pages provide a snapshot of some of the work being done in our department. Feel free to contact individual faculty members and find out more about their research. You can also find more information on our website: www.tifr.res.in/~dcmpms/

We hope you will have fun exploring CMPMS@TIFR!
Nanomaterials Research Laboratory

The NanoLab: What do we study?

Most physical and chemical properties of matter change, often quite drastically, when the physical size of the sample is made smaller than 10-100 nanometer (nm). We are interested in finding out how and why different properties change (“finite size effects”) in nanostructured solids. We try to address and understand simple questions such as:

- Does a superconducting material in the form of a nanoparticle retain superconductivity?
- What is the colour of Silver in the form of nanoparticles?
- How can one make a solar cell out of an array of nanorods?
- Does crystal structure change when particle size is reduced?

Selected results from the NanoLab

Simultaneous ferromagnetism & ferroelectricity in Se microtubes

Multiferroic materials, in which ferromagnetism and ferroelectricity are intrinsically coupled, have generated much interest. We have observed a coexistence of magnetic and ferroelectric ordering in single crystalline Selenium microtubes (Fig. 1) below \( \approx 40K \). This is the first time that multiferroicity has been observed in a simple element. This unexpected behavior arises from Selenium being a ‘surface topological insulator’.


A new form of Silver stabilized by small particle size

By carefully controlling the particle size, we have made a new form of silver with a hexagonal crystal structure (normal silver is cubic) and surprisingly different properties. Hex silver is golden in colour (Fig. 2) and has a high electrical resistance. It is chemically reactive, hard and brittle.


Clustered metal nanorod arrays: Exciting applications

We have shown that an array of parallel, metallic nanorods (Fig. 3) can act as an electrode for ultra-low voltage gas discharge [Nanotechnology 19 (2008) 445713], is an excellent source for field-induced electron emission, as well as laser-induced emission of pulsed, hard x-rays [Physical Review B 83 (2011) 035408].

Experimental Techniques

We make nanoparticles, nanocrystalline thin films and arrays of aligned nanorods by high pressure sputtering, chemical and electrochemical techniques. The nanostructured samples are characterized by high resolution electron microscopy, x-ray diffraction, etc. Physical property measurement techniques involve Raman and optical spectroscopy, electrical transport, magnetism, thermal analysis, and so on.

GROUP MEMBERS:

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Fundamental Optics, THz & Optical Nanostructures

Tools & Techniques

Numerical Design tools: finite difference time domain, rigorous coupled wave analysis, finite element.

Fabrication tools: photo-, e-beam, interference- lithography and wet or dry etching methods.

Optical spectroscopy tools: linear and nonlinear techniques with 1 µm spatial-, sub-nanosec time-, 0.1 nm wavelength- resolution.

Welcome to Foton lab: Plasmonics and Photonics Activity

In the Foton lab we are active in the areas of Plasmonics and Photonics. We investigate light modulation and control of optical properties in nanopatterned metal-dielectric and dielectrics. Broadband response is of particular interest.

Nanopatterns conforming to crystals, quasicrystals or aperiodic patterns are designed to have unique properties. We fabricate and study these structures.

We study light localization for quantum information processing, controlling light emission and light modulation for nanophotonic and optical planar integrated circuits and modulation of optical properties of materials.

Metamaterials (Plasmonic)

Surface plasmon polaritons (SPPs) are charge density waves at the metal-dielectric interface. SPP excitation and resultant strong local field is useful for manipulating the optical properties of materials and light itself. We design, fabricate and study metal-dielectric structures.

With emphasis on light harvesting, broadband and near dispersionless plasmon excitation is demonstrated in plasmonic crystals and quasicrystals.

We demonstrated plasmon mediated giant enhancement of magneto-optical properties. Enhanced light emission from semiconductors and light modulation in plasmonic crystals are some of the topics we are currently working on.

Light reflected at an interface experiences various shifts like Goos-Hanchen, Imbert-Federov and angular shifts. We designed and demonstrated structures that exhibit giant plasmon mediated beam shifts.

Dielectric structures

Photonic crystals, periodic dielectric structures, are actively pursued. PC cavities with quantum dot defects are studied for quantum information processing.

All dielectric metamaterials conforming to Reflectionless potentials are demonstrated for broadband reflectionless transmission.

Cross waveguides about single quantum dots demonstrated for measuring the complete polarization state of the emitted light.

CURRENT MEMBERS:

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Welcome to the Soft Matter Lab!

The soft matter research program is mainly inspired by our experience with interesting but non-intuitive phenomena with everyday materials, such as peeling of paint, sticking of particulate matter to surfaces, formation of cloud, structure and dynamical response of a sandpile. Questions of basic and general nature are extracted from them and experimental methods are devised in order to find precise answers about them in model systems that retain the essence of the original observations. The experimental systems typically consist of building blocks that are larger than atomic dimensions, from ten nanometers to centimeters, both in and out of mechanical and thermodynamically equilibrium. The investigations are aimed to provide deeper understanding of the world around us. We use experimental tools like optical tweezers, various types of rheometry and high speed imaging techniques. We also develop new techniques, experimental protocols and their interpretive framework. The broad aim is to ask interesting questions and devise novel ways to study them.

Highlights from this years work.

**Autotuning of friction:** Self-organization is ubiquitous in nature, although a complete understanding of the phenomena in specific cases is rare. We have elucidated a route to self-organization in a model granular system. From this, a key ingredient for achieving robustness emerges, namely, a continuously variable relative fraction of time the objects spend in two distinct motional degrees of freedom, rolling and sliding. In so doing, they access a large range of effective friction coefficients that allows self-tuning of the system to adjust its response to changing environments and guarantees a protocol-insensitive unique final state, a previously unidentified paradigm for self-organization.

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**Examples of recently studied problems**

- Microscopic understanding of the laws of friction.
- Physics of weakly adhering systems.
- Origin of rigidity in amorphous materials.
- Self-organization in granular matter.
- Electrohydrodynamics in oil-in-oil emulsion.
- Mixing in highly viscous environment.
- Wetting properties of surfaces.
- Dynamical instabilities in bulk fluids and in spatially constrained environment such as random porous media.

Auto-Partitioning of particles into rolling and sliding states, a mechanism via which friction can be self-adjusted by the system.

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Semiconductor Optoelectronics and Nanostructures

(a) TEM cross section of GaN QWs grown on graphene, (b) Luminescence from a GaN QW transferred to a flexible substrate.

Compound semiconductors and devices

Optoelectronic devices – lasers, LEDs, transistors etc. – that drive today’s technological world depend on combining various semiconductors, typically of different bandgaps. These devices have many layers, ranging from few atoms to a few μm in thickness. Semiconductor quantum structures – ultra-thin film, wire, or dot-like configurations of nm size are at the heart of most devices. The growth of compound semiconductors heterojunctions is the first step for devices. Our lab specializes in the epitaxial growth and characterization of bulk and low-dimensional (quantum wells/wires/dots) III-V semiconductors, particularly III-nitrides, and their use in different heterostructures and devices.

Tools & Techniques

We use metalorganic vapour phase epitaxy (MOVPE) for the synthesis of compound semiconductors. We have two MOVPE systems, a horizontal reactor for As/P materials and a 3x2” closed-coupled showerhead system for III-Nitrides, with in-situ optical sensors for growth monitoring. We also use the extensive structural, optical and electrical characterization tools across the department to analyze and understand our materials.

Ongoing research

MOVPE grown III-Nitrides

• Synthesis of semi-polar and non-polar oriented nitrides. HRXRD techniques to characterize epilayers with anisotropic biaxial strain, polarization resolved measurements of optical properties.
• Novel substrates for III-nitrides: MOVPE growth on graphene, MoS$_2$ WS$_2$
• Heterostructures for devices – 2D electron gas layers for HEMTs, InGaN/GaN and AlGaN/GaN QWs for LEDs, etc.
• Growth of nanowires and quantum dots in III-nitrides

Other III-V and 2D materials

• VLS grown nanowires of InAs, InP and core-shell structures
• Study of the 2D-3D transition and the effects of growth kinetics quantum dots (InAs/GaAs, InAs/InP)
• Heterostructures for QW lasers, QW infrared photodetectors
• Synthesis and characterization of bulk and thin-films of transition metal dichalcogenides like ReS$_2$, ReSe$_2$, MoS$_2$, WS$_2$ etc.

Showerhead MOVPE system for the synthesis of III-nitride materials. The system can handle 3 2-inch wafers, and is equipped with an in-situ real-time optical sensors for measuring surface temperature, growth rate, and sample curvature.

CURRENT MEMBERS:

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Nanoelectronics group

What do we do?

The goal of our work is to probe phenomena unique to nanoscale systems. We study:

- How electrons flow through one atom thick graphene
- How heat flows in wires 1000 times narrower than hair
- Why elastic properties of nanostructures are different
- How the spin of electron can be manipulated by its charge

Our work extensively uses the nanofabrication facility at TIFR.

Why we do the things we do?

- To develop design of next generation transistors
- Explore how new sensors of charge, spin and mass can be made
- Understand how quantum Hall effect in graphene is different
- Use spin of electrons is coupled to its angular momentum

Some of the key results from our lab

- Single atom thick "guitar string" nanomechanical resonator
  Used to show that graphene has a negative coefficient of expansion
- Nanoscale transistor
  An efficient wrap gate transistor
- Quantum Hall effect in graphene
  How stable is the quantum Hall state?
Semiconductor Physics using Optical Spectroscopy

What we do

Our research involves the study of electronic band structure of semiconductor materials and physical properties that derive from it. An understanding of such properties is crucial for electronic and opto-electronic device applications. We employ a variety of optical spectroscopy techniques and have studied group III-V semiconductors such as GaN and GaAs families, with emphasis on nanostructures such as Quantum Wells, Wires and Dots. Our recent studies have been on the new class of 2-dimensional mono-layer transition metal dichalcogenide semiconductors such as MoS₂.

Low dimensional semiconductor systems

Semiconductor materials can be grown in nanometer dimensions with high crystalline quality using modern epitaxial growth techniques. The small size can lead to “quantum confinement” of electrons and holes resulting in fewer accessible energy states, unlike continuous energy bands in a 3-dimensional (3D) solid. Such structures can be categorized as super-lattices, quantum wells/wires/dots depending on the number of dimensions in which the carriers are confined. Transition metal dichalcogenides such as MoS₂, which can exist as stable mono-layers, represents another type low dimensional (2D) system.

Quantum confinement can lead to dramatic changes in material properties. For instance the bandgap, a fundamental property of a semiconductor, can change. Sometimes structural changes in nano-materials can lead to interesting effects such as strongly polarized emission from the wurtzite phase of GaAs which form when GaAs is grown in the form a nano-wire (see adjacent figure). Understanding such properties is essential for designing semiconductor devices, especially opto-electronic devices such as lasers and light emitting diodes, with significantly improved characteristics. We use optical spectroscopy to study such electronic band structure changes where we glean information from not just the photon energy, but also from the material’s sensitivity to the polarization state of light.

Tools & Techniques

We use spectroscopic techniques such as absorption, reflection, Raman, photo/electro luminescence, photo-voltage/current and modulation techniques such as electro-reflectance, ellipsometry and magneto-optic-Kerr-effect spectroscopy. The setups we have built consist of monochromators, light sources including lasers, detectors, specialized optical components and measurement electronics. Measurements can be done in the wavelength range of 250nm - 14000nm covering the UV-VIS-NIR-MIR-FIR range. The sample temperature can be varied in the range 4.5K - 400K in magnetic fields up to 7T, with high spatial resolution down to ~1.5µm.

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We study the electronic structure (the arrangement of electrons in various energy levels) experimentally to reveal the microscopic origin of varied interesting electronic properties of correlated electron systems, superconductors, topological insulators, diluted magnetic semiconductors etc. Some of the examples are given below.

**Fe-superconductors**

Superconductivity and magnetism are two mutually exclusive phenomena. Still compounds having a magnetic element, Fe show superconductivity. Here, Superconductivity appears on destruction of magnetic order. Interestingly, some material such as EuFe₂As₂ shows coexistence of both. Here we show that electronic states taking part in superconductivity seem to get influence by magnetic order.

**Topological Insulators**

These are interesting materials having a special kind of metallic surface states protected by the insulating states in the bulk and cannot be altered by external parameters. A typical energy band dispersion of such a material show Dirac cone [Dirac point (DP)] for the surface electrons, which provide dissipationless charge transport. However, behavior of these materials are different from the ideally predicted ones. There are several issues to be resolved before these unusual surface states of these materials can be utilized for technological advances or to realize long standing fundamental physics.

**Strongly correlated systems and Kondo Physics**

Coulomb repulsion between electrons is often the key reason behind all unusual material properties including unconventional superconductivity. Magnetism is a great manifestation of such effect. If the magnetic electrons hybridize with the mobile electrons, a non-magnetic phase may appear leading to lots of anomalies in their electronic properties, which is known as Kondo effect. We play around with this coupling in real materials and investigate their interesting electronic and magnetic properties.

**CURRENT MEMBERS:** Kalobaran Maiti, Khadiza Ali, Tanusree Saha, and K. Srinivas

Lab: BG37 url: [www.tifr.res.in/~peslab/](http://www.tifr.res.in/~peslab/)  
PhD positions available
Fundamental Optics, THz & Optical Nanostructures

Welcome to Foton Lab: THz Activity

In Ultrafast Optics and Tera-Hertz (THz) Spectroscopy activity, Foton lab at TIFR primarily investigates ultra-fast phenomena, carrier dynamics and various optical phenomena involving THz radiation. Several biological and chemical molecules have vibrational frequency lines falling in the THz regime. Several materials exhibit exotic properties which are due to their rearrangement of charge carriers. These properties change with temperature, electric field or magnetic field or under optical fluence. THz radiation measures conductivity these carriers. Our lab aims to tackle the basic challenges to understand these processes with homebuilt sources, detectors and setups.

THz Spectroscopy (10^{12} Hz)

The THz radiation has wavelengths from 30 microns (10THz) to 1000 microns (0.3THz) as opposed to visible (0.4 to 0.7 microns). This is the final frontier in electro-magnetic spectrum which needs to be explored in terms of high power sources, sensitive detectors and spectroscopy setups. One of the central challenges in building such a system is, high intensity sources or detectors are not available. We don't yet know how to make them! So we try various designs for increasing the THz emission and detection efficiency. This requires study of several different types of materials and charge carrier dynamics in them is possibly the key for solving this problem. The spectroscopy has several applications from medicine to condensed matter physics and the field is wide open.

Applications

Some of the exotic materials or molecules have very interesting properties which are related in turn to the way charge carriers are arranged or the way they respond to external stimulation. THz spectroscopy can tell a lot about conductivity response of such carriers. We can record the amplitude of the THz light field, how it oscillates in femtosecond (10^{-15} sec) time scale. When passing through the sample it changes appropriately revealing all the information. We are interested in studying this information and improve our understanding.

Two home built THz setups for performing transmission (box enclosed) and reflection THz.

Tools & Techniques

Our experiments are carried out at temperatures varying from 320K up to 10K, achieved using a closed cycle helium refrigerator. The THz (antenna) sources and detectors are made out of Gallium Arsenide (GaAs) wafers using conventional photo- or nano-lithography in a cleanroom. We use ultra-short pulsed laser (10fs, 800nm, 80MHz) for exciting carriers in GaAs to generate THz signal. The generated THz pulse (~1ps duration) is used to study our samples. We also fabricate necessary components for THz optics which are not available.

CURRENT MEMBERS:
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India’s First THz Image of Father of our nation which we have taken in our lab in TIFR from 500Rs currency watermark.

A Typical THz Pulse waveform recorded in our laboratory. The entire pulse duration is in few picoseconds.
Welcome to Superconductivity lab

The Superconductivity lab in TIFR is primarily involved with the study of novel ground states that emerge as a result of interaction and disorder in conventional and unconventional superconductors. Our main workhorse, are two state-of-the-art home built scanning tunneling microscopes (STM), operating down to 300 mK and in magnetic fields up to 9T. We complement STM measurements with transport and magnetic measurements in different frequency domains, ranging from dc all the way to microwave. We also use these techniques to look at systems other than superconductors, such as charge density waves and magnetic systems. (more details on website)

Scanning tunneling spectroscopy

The scanning tunneling microscope (STM) relies on quantum mechanical tunneling of electrons from the surface of the sample to an atomically sharp tip, to obtain an atomically resolved image of the surface. However, the greatest advantage of an STM stems from its ability to simultaneously capture spectroscopic information through the measurement of tunneling conductance, with atomic spatial resolution and unsurpassed energy resolution (<100 µeV). This makes STM particularly suited to study correlated electron systems, including superconductors where exotic electronic states emerge from subtle redistribution of electrons within few meV around the Fermi energy. The TIFR STMs combine, in-situ thin films growth and surface preparation capability, such that measurements can be performed on pristine surfaces, uncontaminated from exposure to air.

CURRENT MEMBERS:

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Schematic view of the 350 mK scanning tunneling microscope at TIFR.
Correlated Electron Systems: Oxides/Intermetallics

Welcome to our lab

Competing interactions plays a crucial role in controlling the physical properties of materials, making this field of research lively. In our laboratories, apart from focussing on discovering novel materials, we investigate how various phenomena of great current interest compete by changing temperature, external and chemical pressure, magnetic fields and particle size. Some of the topics of current interest are: (i) Competition between magnetic ordering and the Kondo effect (in the field of "Heavy fermions"), which favours non-magnetism; (ii) Competition between magnetism and ferroelectricity ("multiferroicity"); (iii) What happens to the spins arranged in a triangular fashion which are coupled antiparallel to each other (leading to what is known as "geometrically frustrated magnetism")? A comparison of the properties of materials in bulk and single-crystalline forms with those of nanocrystals has been found to be valuable to understand some of the issues in the field. Apart from these, topics relevant to applications like magneto-caloric effect are also being undertaken.

Highlights

The f-electron anomalies in bulk form:

Evidence for the validity of spin-density-wave picture (as against 'local-moment' picture) as quantum critical-point is approached - a major issue in the field of 'heavy-fermions', (PRB 82, 104428 (2010)). Anomalous magnetic ordering in a Nd-based intermetallic compound, emphasizing the need to explore strong electron correlation effects in Nd systems (PRB 84, 184415 (2011)).

Huge enhancement of magnetoresistance, with a positive sign which is unexpected at the metamagnetic transition; possible 'Inverse metamagnetism', an interesting new concept (e.g., PRB 79, 060403(R) (2009); PRB 80, 214425 (2009); PRB 81, 184434 (2010)).

Particle-size effects in intermetallics:

First demonstration of particle-size induced ferromagnetism in an exchange-enhanced "Pauli paramagnet" like YCo$_2$. Interestingly, f-electron electron localization leading to magnetic ordering has been reported even for (non-magnetic) Kondo lattice. (APL 92, 192506 (2008); PRB 80, 024401 (2009)).

Spin-chain magnetism:

Identification of anisotropic spin-glass anomalies and spin-chain magnetism (TbPdSi$_3$), unusual among among intermetallics (PRB 67, 212401 (2003)).

Magnetoelectric coupling and multiferroicity in a Haldane spin-chain system (PRB 88, 094438 (2013)).

In Ca$_3$Co$_2$O$_6$ and its derivatives, we reported evidence for hitherto unrealized 'incipient' spin-chain ordering at a temperature much higher than Néel temperature, coupled with phonon and magnon anomalies! A rare phenomenon of "spin-chain-induced multiferroicity", that too, above 77 K, was discovered bearing relevance to applications (PRB 77, 172403 (2008); 79, 094103 (2009); JAP 108, 103517 (2010); (Nature Group) Sci. Rep. 3, 3104 (2013).

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Tools & Techniques

We have facilities to synthesize the materials in bulk form, single crystal and nanoform. Many experimental facilities down to subhelium temperatures and high magnetic fields exist in our laboratories - heat-capacity, magnetization, electrical resistivity thermopower, complex dielectric properties and electric polarization and Mössbauer spectroscopy. In addition we collaborate with other labs for studies like neutron diffraction, Raman and Photoelectron spectroscopy. Several department facilities like TEM, SEM, XRD are available for characterizing the materials. We also specialize in performing electrical resistivity and magnetization under high pressure.
**Tools & Techniques**

Single crystals are grown using a variety of methods. A tetra-arc furnace and an optical floating zone furnace are the main workhorses to grow single crystals by Czochralski and floating zone methods apart from the usual box type furnaces to grow single crystals by flux method. A Laue diffractometer to orient the single crystals. A physical property measurement systems (PPMS) with a 14-T magnet to measure specific heat capacity and electrical resistivity down to 50 mK using the dilution insert.

**CURRENT MEMBERS:**

Prof. S. K. Dhar and Prof. A. Thamizhavel; Ms. Ruta Kulkarni, Mr. Arvind Maurya, Dr. Arvind yogi and Dr. Md. Matin

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**Welcome to Crystal Growth lab**

The main theme of the crystal growth lab is to grow the single crystals and study the anisotropic physical properties of strongly correlated electron systems (SCES). The single crystals are grown by employing different crystal growth techniques like Czochralski method, Bridgman method, high temperature solution growth and vapor transport methods. The grown crystals are oriented along the crystallographic directions by means of Laue diffraction and cut along the crystallographic directions by means of spark erosion cutting machine for the anisotropic physical property measurements.

**Strongly correlated electron system (SCES)**

In some of the intermetallic compounds, the conduction electrons interact very strongly with the magnetic atoms present in the system and hence the magnetic ordering of the magnetic atoms is suppressed and the magnetic character of the atoms is *dragged* along or hybridized with the conduction electrons. Such types of systems are classified as SCES. The competition between the long range magnetic order and the itinerancy of the electrons on the magnetic atoms leads to diverse ground states. Ce and Yb-based intermetallic compounds are studied quite extensively by growing the single crystals of these compounds.

**Quantum Phase Transition**

The magnetic phase transition occurring at finite temperature of the SCES of mainly cerium or ytterbium compounds can be continuously tuned from a magnetically ordered state to a non-magnetic ground state by a non-thermal external control parameters such as high pressure, composition or magnetic field. For a critical value of the control parameter, the magnetic phase transition approaches a $T = 0$ phase transition or the so called quantum phase transition (QPT) which separates a magnetically ordered from a non-magnetic ground state at zero temperature. One of the objectives of this laboratory is to look for such materials that exhibit QPT.
The Quantum Measurement and Control Laboratory (QuMaC) at TIFR primarily investigates quantum phenomena in superconducting circuits. These nanofabricated electrical circuits are engineered to behave as “artificial atoms” with quantized energy levels. Two of those levels can form a quantum bit (qubit) and used to store and process information. With such qubits, one can build powerful computing machines capable of providing exponential speed up for certain mathematical problems. Our lab aims to tackle the basic challenges in building and controlling such quantum systems.

Quantum Feedback Control
One of the central challenges in building a quantum computer is that the qubits do not maintain their quantum nature for a very long time. This phenomena is called decoherence and happens primarily due to environmental noise. However, it is possible to use multiple imperfect qubits to build a near-perfect qubit using a process called quantum error correction. This involves encoding the single qubit state among multiple physical qubits, making the right kind of measurements to detect any errors and then use feedback to correct those errors. We are investigating techniques to implement quantum error correction using weak continuous measurements and feedback. This will involve ultra-fast signal processing using Field Programmable Gate Arrays (FPGA).

Quantum Simulations
The computational resources required to simulate quantum mechanics on a classical computer grows exponentially with the size of the simulated system. Feynman had originally suggested that one should use quantum systems to simulate quantum mechanics. The basic idea is to have a well characterized and controllable quantum system to mimic the behaviour of other systems of interest. Our lab is interested in studying collective behaviour in superconducting qubits and developing the necessary architecture for performing quantum simulations.

Tools & Techniques
Our experiments are carried out at cryogenic temperatures of around 10 mK, achieved using a dilution refrigerator. The superconducting circuits are made out of aluminium on silicon or sapphire wafers using nanolithography in a cleanroom. We use microwave frequency (4 – 8 GHz) signals to manipulate and measure our devices. We use high speed digitizers and FPGAs to record and process the measurement signals at GHz rates. We also design and build custom microwave frequency amplifiers, filters, attenuators and circuit boards.