Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

EDITOR’S DESK

The second issue of this year 2016, guest edited by Professor Aveek Bid and Professor Anindya Das, Department of Physics, Indian Institute of Science brings out state of the art reviews on the topic ‘Transport in Mesoscopic Systems”.

The first review article encompasses a pedagogic review on Designing Model Topological Insulators, a centuries old concept, providing a holistic overview on methodologies, computational schemes, and engineering principles. The review on Spin Polarization of Majorana Zero Modes and Topological Quantum Phase Transition in Semiconductor Majorana Nanowires is an account of recent work on the issue of spin polarization. Nanomaterials and Crystals of Topological Insulators describing a new class of materials exhibiting exotic surface properties form the theme of the next review article. Electrical Transport in Vanadium Dioxide is the topic of discussion in the next review, while Spin Polarised Tunneling Probe for Two and Three Dimensional Dirac Metals is the subject of the next discussion. A Short Review is an introduction and a discussion of Weyl fermions as emergent particles in condensed matter systems brings in the flavour of a new area in transport phenomenon.

I extend my sincere thanks to Professor Aveek Bid and Professor Anindya Das for Guest Editing Vol. 96 No. 2 of the Journal of the Indian Institute of Science and all the authors for their valuable contribution towards the compilation of this issue. My special thanks to the editorial team who as always put in an enormous effort to get the articles ready for publication.

T.N. Guru Row
Editor
ssctng@sscu.iisc.ernet.in

Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

Transport in Mesoscopic Systems

One of the most important questions in current condensed matter research is what happens when the size of the current carrying conductor begins to approach the characteristic length scales of the system like mean free path, Fermi wavelength and coherence length. For devices whose sizes are of the order of the phase-coherence length, quantum effects start to play an important role and the devices have to be treated as quantum systems. Such systems are said to lie in the 'mesoscopic' range—their typical length scales are somewhere between the size of an atom and a few micrometers. The word mesoscopic originates from the Greek root which means 'intermediate'—the field of mesoscopic physics is thus the study of objects which lie in the regime between microscopic and macroscopic dimensions. In recent years, semiconductor nanostructures of reduced dimensions (in the form of two dimensional electron gas, one dimensional nanowires and edge states or zero dimensional quantum dots) have become the model systems to study in this 'mesoscopic' regime. This is driven by the availability of semiconductor materials of unprecedented purity and crystalline quality and by the ability to band-engineer these materials to produce a thin conducing layer of highly mobile electrons sandwiched in a quantum well. As the lateral dimension of the well is much smaller than the characteristic lengths of the system, the motion in this direction is quantized and the charge carriers can be made to move in a plane. This forms a model two dimensional electron gas (2DEG) which has a number of desirable properties not found in thin metal films. The density of the 2DEG can be made quite low and, due to the large screening lengths can be tuned readily by applying an external electric field. The low density ensures a large Fermi length (~40 nm) comparable to or larger than the size of the nanostructures that can be routinely fabricated today. The defect free nature of the parent semiconductors ensures a large mean free path (~ few tens of microns). The reduced dimensionality of the system and the circular Fermi 'surface' make theoretical studies easier in these systems as compared to most metallic systems. It is also fairly routine to form 1-dimensional and 0-dimensional structures out of these 2DEG using electrostatic gating thus enabling the study of the effect of dimensionality on the physics of mesoscopic devices.

A variety of experimental techniques are employed today to investigate the fundamental quantum phenomena in such nanostructures. These include high resolution Angle resolved photoemission (ARPES), Scanning tunneling microscopy, optical absorbance and emission spectroscopy electrical transport. At very low temperatures the quantum mechanical wave character of the electrons and their Coulomb interactions lead to exciting phenomena- Superfluidity, Superconductivity, Integer Quantum Hall Effect, Fractional Quantum Hall Effect and Topological spin Hall Effect to name just a few. The discoveries of these exotic states of matter have come not only with many potential applications but have also enriched our understanding of physics at the most fundamental level. They have been the result of (and in turn have led to tremendous advances in) technological breakthroughs in experimental techniques and the development of new theoretical tools to deal with strongly correlated many-body systems. Recently, there has been an increased activity in this field driven by the ability to routinely achieve ultra-low temperatures in the laboratories and the availability of high quality devices. This has led to the emergence of exciting new materials like graphene and two dimensional electronic systems at oxide-oxide interfaces with properties not seen in conventional semiconductors. New physics is being studied with lot of potential applications like Bloch oscillating amplifiers, Quantum computers and spin transfer torque based magnetic tunnel junctions.

Transport in the mesoscopic regime shows many interesting features not found in classical diffusive transport. At low enough temperatures and for clean enough devices, electrons can propagate for distances over few tens of microns without losing their phase coherence. At one end of the spectrum is the regime where the elastic scattering time is smaller than the phase coherence time τ is smaller than the

Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD
© Indian Institute of Science

phase coherence time τ_ϕ (which is determined by inelastic scattering). Elastic impurity scattering cannot destroy phase coherence, which is why the effects of quantum interference can modify the conductivity of a disordered conductor. This is the regime of 'diffusive transport' where quantum interference becomes more and more important as the dimensionality of the conductor is reduced. Among the many important physical phenomena seen in this regime are weak localization, Universal conductance fluctuations (UCF) and Aharonov-Bohm effect. Whereas for classical diffusion, correlations in the diffusion process due to quantum interference disappear on the time scale of the scattering time τ in quantum diffusion correlations persist up to times of the order of the phase coherence time τ_ϕ. As an example, consider the temperature dependence of a two dimensional electron gas of moderate mobility—as the temperature is decreased down from room temperature, initially the resistance decreases monotonically with temperature due to suppression of the phonon scattering rates, eventually saturating to a value that is determined by the amount of elastic scattering by static impurities. In very narrow conductors however, it is seen that below a certain temperature the resistance begins to increase again as the device is cooled—this anomalous increase in the resistance is due to long range-correlations in the diffusive motion of the charge carriers (elastic scattering being ineffective in destroying phase correlations in the phase of the electron wave functions) and is a purely quantum mechanical effect.

At the other end of the spectrum is 'ballistic transport' in which scattering with impurities can be neglected and transport is limited by the boundaries of the device rather than the presence of impurities. In such systems, the idea of a local conductivity breaks down and unlike in the diffusive transport regime, here the Einstein relation between conductivity and diffusion constant at the Fermi energy can no longer be used. Instead conductance is described in the term of the Landauer formula which treats electrical transport in ballistic systems as a transmission problem and relates the conductance of the system to the number of transmission modes at the Fermi energy. Conductance quantization in a quantum point contact, electron focusing by an applied weak magnetic field and electron collimation are some of the fascinating phenomenon seen in this regime.

The study of transport in mesoscopic conductors of reduced dimensions is very important not only from a pure academic point of view but also to the semiconductor industry where the sizes of actual devices are already approaching sizes of the order of 10 nm. The fabrication of mesoscopic structures relies on the availability of ultra-pure semiconductor wafers and on the development of specialized lithographic techniques that exist because of the effort put in by industries towards the miniaturization of transistors, the development of faster and cleaner interconnects and the hope of developing new devices based on the principles of Quantum mechanics. Conventional transistors which are meant to work in the regime of classical diffusive transport break down when the channel dimensions begin to approach sub-micron sizes. The novel transport regimes in semiconductor nanostructures, as outlined above, provide options for the development of innovative future devices.

At the end we will discuss about the impact as well as emergence of mesoscopic physics for last ten years. The current issue is about those topics like metal-insulator transition, topological insulators, Majorana quasi-particle, Weyl-semimetal and Dirac fermion etc. These are all part of some kind of insulators. We know from our graduate level of physics that due to the periodicity of lattice we have band gap opening in the electronic band structure and the material will be insulator if the bands are completely filled with the electrons and these are known as trivial insulator. Otherwise insulator also can arise due to strong correlation effect like in oxides etc. However, the surface states of these trivial insulator does not conduct. It has been now demonstrated that one can make the special insulator (bulk) with the band inversion or some other way such that the surface states of the insulator will conduct. These surface states of non-trivial insulator also have special protections like spin-momentum locking etc such

Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

that the back reflection becomes suppressed. Another interesting consequence is that the dispersion is relativistic type. Similar to non-trivial or topological insulator there are new type of superconductor or topological superconductor has emerged, where the existence of Majorana quasi-particles has been proposed. Majorana fermions are the only fermionic particles that are expected to be their own antiparticles. While in high-energy physics the Majorana is an elementary particle, in condensed matter physics one of its manifestations is an emergent quasi-particle at zero energy state. This issue of the Journal of the Indian Institute of Science gives a preview of this new and exciting field of physics.

Prof. Aveek Bid
Department of Physics,
Indian Institute of Science,
Bangalore 560012,
India.
aveekbid@gmail.com

Prof. Anindya Das
Department of Physics,
Indian Institute of Science,
Bangalore 560012,
India.
dasanindy@gmail.com