Nanotechnology at IIT Bombay

Introduction: Nanotechnology, an emerging interdisciplinary field involving development of nanometer sized materials, devices, and systems, finds revolutionary applications in almost all fields of sciences and engineering. Nanotechnology research in IIT Bombay (IITB) can be broadly classified into (i) nanomaterials, (ii) nanoelectronics, nano opto-electro-mechanical systems (NEMS), and nanomagnetics, and (iii) nano biotechnology, resulting in a wide range of applications. This document summarizes these applications, and the current research activity that is taking place. The research activities are being carried out in collaboration with Indian and international institutions. The funding has been forthcoming from several agencies that include ADA, MHRD, MBT, and DST. There exists excellent infrastructural support, which includes a Class 100 cleanroom (Electron Beam Lithography, Multi-Target Sputterer, Reactive Ion-Etch, Hot-Wire and Plasma Enhanced CVD), and characterization facilities (Transmission and Scanning Electron Microscopy, Atomic Force Microscopy, X-Ray Diffraction, Orientation Imaging Microscopy, X-Ray Texture Goniometer, Electron Spectroscopy for Chemical Analysis).

I. Nano-materials

Currently, nanoparticles (grain size ~ one billionth of a meter) find use in areas such as catalysis, paints and pigments, cosmetics, drug delivery, non-linear optics, photonic crystals, fuel additives, magnetic recording materials, electronics, NEMS, and bioscience and engineering. In addition, these particles may serve as building blocks to the manufacture of nanodevices which forms a major effort in nanotechnology. Nanoparticles can be prepared by using a number of methods. The physical methods include techniques like the comminutions, vaporization-condensations and laser techniques. The chemical methods include reactions in vapor phase followed by condensations and the decompositions of precursors, soft chemistry techniques such as sol gel, autocombustion, microwave refluxing, and some bio mimetic and glass ceramics methods. The methods based on surfactants and interface sciences are the sol-gel technique and the microemulsion methods and these methods have been extensively used at IITB to produce nanoparticles of metals, metal oxides, metal salts and compounds, and polymers at room temperature and pressure. Work on the synthesis of monodispersed nanoparticles using supercritical carbon dioxide is also in progress.

There is a considerable activity on the synthesis/formation of **nanoclusters** and their confinement in the cavities/voids/pores of nanoporous inorganic matrices. Cluster chemistry constitutes one of the most important aspects of investigations from the bottom-up perspective in nanoscience research, using techniques borrowed from atomic and molecular sciences to drive assembly of larger structures in a coherent fashion. New synthetic procedures have been used for covalently assembling nanoscale discrete molecular architectures with desired functions. The novel mixed-metal, non-metal clusters have been designed, structurally characterized and their molecular structures identified in detail. Further, some of their unusual properties resulting from large molecular size and unprecedented electronic framework arising from incorporation of different types of framework atoms have been examined, specifically related to catalysis, organic transformations and optical properties.

Confinement of nanoclusters and nanoparticles in mesoporous materials have been another active area. They are highly conducive for a number of important applications such as separation technology, heterogeneous catalysis, and sensors. Several metal oxide nanoparticles including TiO_2, Fe_2O_3, ZnO, and PbO have been prepared within the pores of mesoporous MCM-41 and MCM-48 molecular sieves. In the case of Fe_2O_3/MCM-41 system, it has been demonstrated that both paramagnetic and super-paramagnetic species co-exist.

II. Nanoelectronics, NEMS, and nanomagnetics

This section is concerned with the application of nanotechnology for information processing and information storage. The activities are focused on nanoelectronics (Transistors, LEDs, Solar Cells) and nano opto-electro-mechanical systems (Bio-Sensors etc.), and on magnetic and magneto-resistive materials processing.

One area of activity is focused on nano-crystalline silicon (nc-Si) with grain size less than 10 nm, which can be applied as window layers in solar cells and for nano-devices such as micro cantilevers and micro motors.

The **nano silicon CMOS Transistors** activity is concerned with the development of advanced process steps and modules for sub-50 nm CMOS FETs. The idea is to employ novel unit processes and to integrate them to realize an ultra-short channel nano CMOS device. Specific process steps that are being developed are low-stress silicon nitride layers as gate dielectric, gate material engineering, and plasma ion-implantation for very shallow source/drain junctions.

The **carbon nanotube (CNT)** based device activity is focused on applications in storage devices such as ultra-capacitors, and solar cells. More recently, the promising CNT applications in high performance logic devices and NEMS is also being explored. CNT properties are closely linked to their shape and size. A significant breakthrough will result if metallic and semiconducting CNTs can be produced at low cost, and localized on silicon (and other) planar substrates. The preferred CNT growth process is Chemical Vapour Deposition (CVD). The CVD process allows for specificity of single-wall or multi-wall nanotubes through appropriate selection of process gasses. Decomposition of the feed gas occurs only at the catalyst sites (metal nanoparticles- Zn, Fe, or Mo), reducing amorphous carbon generated in the process. Decomposed carbon molecules then assemble into CNTs at the catalyst sites. A significant goal is to pattern catalyst nano-particles on a substrate lithographically, to seed a specific type of CNT growth at intended locations.

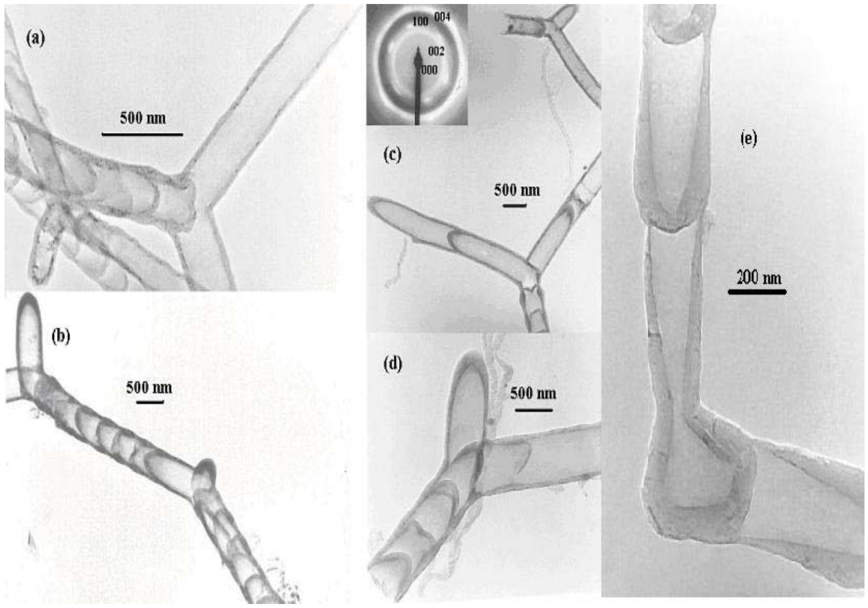

Fig.1 Carbon nanotube structures

The development of **organic molecular structures and systems (OMOS)** involves (a) study of molecular organization of prototypic amphiphilic molecules at air-water interface and in Langmuir-Blodgett mono-layers and multi-layers, and (b) development of semiconducting sulphide nanoclusters in organic multiplayer matrix and ultra-thin, nanocrystalline oxide films from organic multiplayer precursors, and nanocomposites based on conducting polymers. Some of these systems have been used to fabricate light emitting diodes and bio-sensors.

The development of **NEMS Bio-sensors** involves fabrication of integrated cantilever arrays for detecting markers for Acute Myocardial Infarction (AMI) - cardiac muscle damage that accompanies a heart attack. The vision is to develop field-portable, high-throughput, protein detection systems as a common platform for characterizing a wide spectrum of diseases. An advantage of such a *"protein-chip"* is that it detects multiple markers in a single reaction, whereas currently available assays require a separate reaction for each analyte. Thus the cost of performing a cantilever assay can be potentially much lower.

The current effort is focused on fabrication of integrated polymer-nanocrystalline silicon based cantilever arrays. These cantilevers will be equipped with piezo-resistor grids with dimensions varying from 10 nm to 100 um. The cantilevers will provide sites that will bind the proteins in question. The resultant mass or stress induced deflection will be sensed optically, as well as through a change in resistance. Other necessary components will be fluidic systems, reservoirs etc. The follow-up development will involve design and fabrication of cantilever arrays with nanometer-scale embedded elements (such as resistors) and an integrated nano CMOS circuit for electrical resonant detection. Theoretical studies have predicted that for a 1 Hz frequency resolution the minimum detectable mass change is ~10^{-18} g for such Nano Systems.

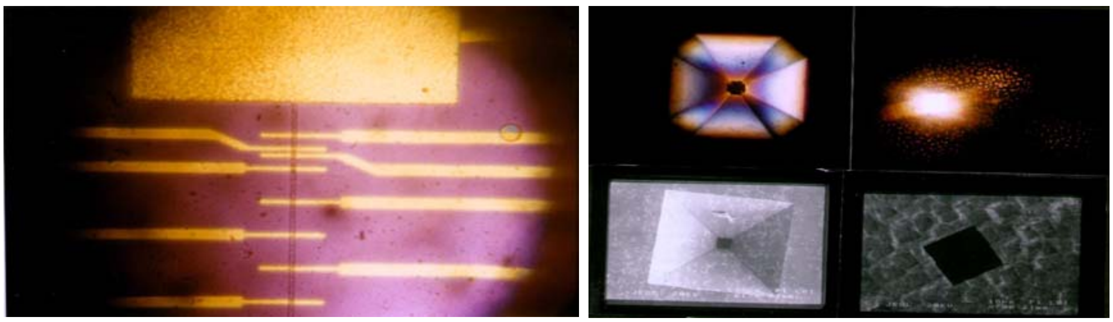

Fig. 2a) Top-view of a Bio MEMS micro-capillary electroporator (uCE) system, 2b) SEM image and Micrograph of a micro-pore as part of the uCE system.

Alternative NEMS fabrication strategies are being developed such as structuring glass using a combination of UV-light and annealing on the other hand offers possibility of making 3-D nanodevices.

Among the existing methods of characterizing NEMS, optical measurement methods are the most accurate, noninvasive and nondestructive. Work in this area at IIT Bombay is going on for developing a platform for facilitating development and calibration of computer-controlled measurement systems with moving optical elements. The platform will be used to develop and test new techniques of optical measurements. The activity will be used for measurement and calibration of bio-sensors and robotic systems.

Encapsulation and packaging are show-stopper issues for OMOS and NEMS devices noted above, where tolerance for humidity and oxygen is extremely low. Recently initiated activity in this area involves characterization of polymer/ceramic nano-scale coating stacks, where the polymer layers provide for an "atomistically smooth" (r.m.s. surface roughness < 1 nm) planarization layer, and the ceramic layers act as moisture/oxygen barriers.

Photonic crystals are novel nanostructures that are used in photonic crystal fibers for dispersion compensation in fiber-optic communication, for very sharp bending of light in optical ICs and in zero-threshold lasers. Theoretical base for carrying out experimental work on these crystals have been established at IIT Bombay. The experimental work will involve synthesis of organic samples of photonic crystals by self-assembly followed by characterization.

Ultra thin films and multi-layer reflecting mirrors useful for x-ray optics are being developed. The research is focused on the physical processes that govern ultra thin (1-2nm) films formation which in turn control the physical properties including optical and electronic. A highly versatile Pulsed Laser Deposition technique is used to form these films.

The properties of **nanostructured magnetic materials** change markedly with decreasing size and offer significant possibilities for novel devices. Currently, the focus is on preparation and characterization of a series of multilayers. Ferromagnetic layers will be chosen among Fe, Ni, and Co alloys, as certain compositions of these alloys exhibit outstanding soft magnetic properties. Nano composites of the above with non magnetic and non conducting systems such as SiO_2, Al_2O_3 and ZrO_2 are being investigated for the possibility of enhanced magneto resistance. Magnetites that offer very interesting magneto transport properties in nanosized dimension are being pursued. One interesting application of magneto-resistive materials is Spin Valves, where the magneto-resistance of the samples can be easily changed by applying external magnetic fields. Spin Valves can be used in a variety of devices like Magnetic Random Access Memories (MRAM), magnetic read heads, magnetic sensors, nonvolatile magnetic memories, etc.

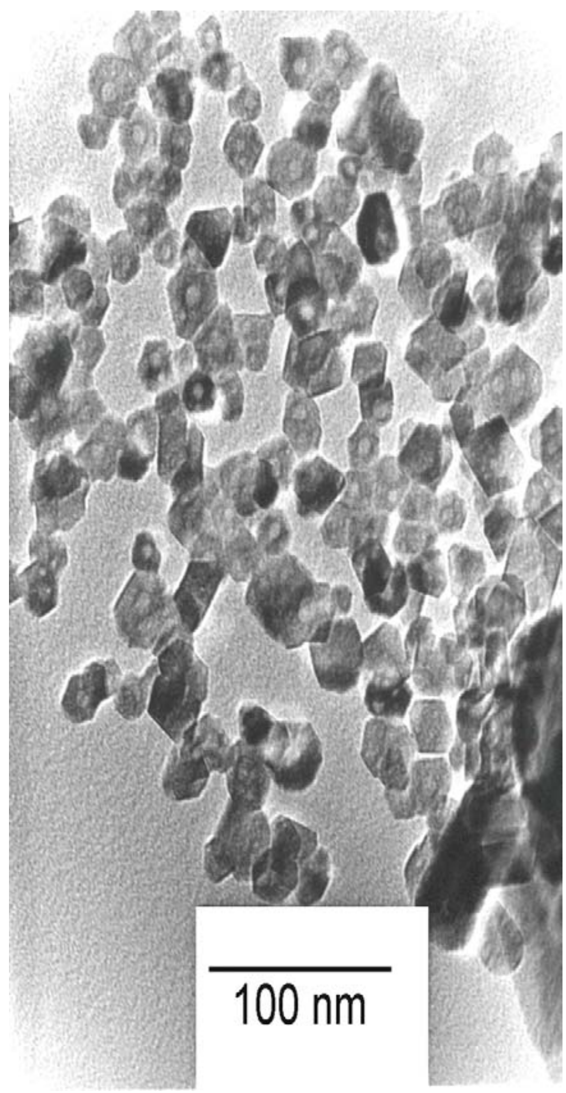

Fig. 3 TEM micrograph of NiZn ferrite

III. Nano biotechnology

Interdisciplinary research applying the principles of nanotechnology in biology and the health care system comprise the nano biotechnology focus at IIT Bombay. Our activities are directed towards development of therapeutic biocompatible nanoparticles for treatment, use of nanoparticles as drug delivery agents, and development of biomaterials and devices for biological applications.

Nanoparticles for hyperthermia in cancer- A promising therapy for cancer is being pursued which is based on the development of magnetic nanoparticles with suitable properties for hyperthermia. The nanoparticles will be specifically localized to the desired site of action. The magnetic properties (losses, saturation moment, and temperature coefficient) of the particles in the presence of an external alternating magnetic field will be exploited to our advantage for hyperthermia therapy.

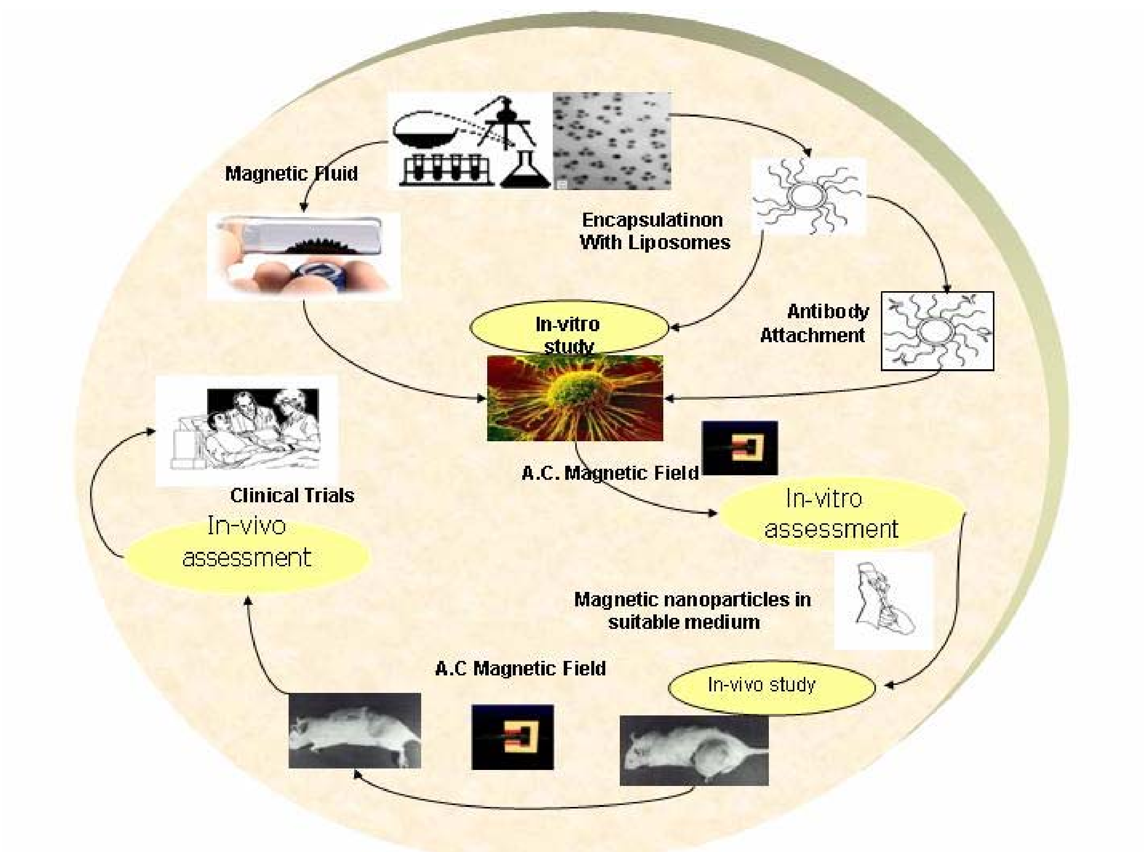

Figure 4. Schematic diagram showing magnetic nanoparticle based hypothermia treatment

Nano-particles for respiratory diseases- A unique complex of nanoparticles, called the pulmonary surfactant, lines our lungs. This material prevents the alveoli from collapsing during expiration and decreases our work of breathing. Surfactant may be quantitatively and/or qualitatively dysfunctional in various respiratory diseases. A replacement surfactant would be beneficial for the therapy of such diseases. Presently, we are developing surfactant nano-particles for inhalation in Neonatal and Adult Respiratory Distress Syndromes (NRDS and ARDS resp.).

Nano-particles as bioactive agents: The Bhasma concept- There exist in the Ayurvedic and Siddha systems of medicine, therapeutic preparations called Bhasma which are extremely fine powders coated with herbal extracts. Presently we are interpreting the therapeutic efficacy of Bhasma preparations in the light of the emerging knowledge on the role of nanoparticles in drug delivery. The physico-chemical characteristics of selected Bhasma samples will be evaluated and a relationship between the physico-chemical parameters and activity will be sought. The idea is to combine the wealth of knowledge of Bhasma technology Indian traditional science and analyze it in the light of nanotechnology characterization.

Nanocomposites for dental and maxillofacial use- Bone defects in periodontal diseases or due to major traumatic injuries require bone replacement. A good approach to bone substitution is to develop nanocomposites based on hydroxyapatite and bioglass ceramics. In order to improve the toughness of the bone substitution materials, hydroxyapatite is being re-inforced with bioglass, zirconia and carbon fibres. Our work deals with the synthesis and characterization of bioglass and hydroxyapatite powders and their subsequent consolidation into various nanobiocomposites.

*Nanopores formed by soluble proteins in membrane vesicles- S*oluble protein toxins in membranes, most notably the alpha hemolysin from Staphylococcus aureus and Diphtheria toxin, have the potential to form stable pores in oriented lipid membranes. These nanopores are formed by oligomerisation of the parent toxin monomers. Such nanopores have strong implications in the fabrication of nanodevices. The pores can be varied in size by chemical modification of the monomer. The formation of such ion-selective channels in lipid membranes provides for a communication medium in nanodevices.

Micro-engineered biomedical devices for transcatheter and endoscopic surgery- The ductus arteriosus represents a communication between the aorta and the pulmonary artery. The rationale for closure is usually to prevent complications such as infective endocarditis and heart failure. We are developing a new device for this condition, which can be delivered by transcatheter technique. This device will help us evolve a miniaturized system of delivery and will be of use in closure of ductus arteriosus.

Summary: The activities in nanostructural materials and devices at IIT Bombay include materials for electronic, magnetic, optical, bio, catalytic, and mechanical devices and applications. In the last couple of years, this activity has greatly expanded which is reflected in new sponsored projects in this area and a large number of publications. The nanoelectronics, nanomagnetics, and NEMS activity are focused on developing the next generation information processing and information storage solutions. A significant development proposed in nanoelectronics is the *molecular assembler*, a device that *can mass-produce other nanodevices on demand*. Such devices include a nanorobot that will allow a heart surgeon to perform surgery without having to open the patient's chest, or a brain surgeon to remove a tumor from behind a computer monitor. Nanoelectronics may also find a way to mimic the working of a human brain- for example, *DNA transistors* that can replace both the conventional transistor and the conventional memory. The activities in the new interdisciplinary area of nano biotechnology can provide means to construct novel molecular architectures with great precision and flexibility. The application of the techniques of nanotechnology, nanoemulsions and molecular self-assembly can be used to create systems that closely mimic biology. This can pave the way for promising and as yet much unexplored avenues of diagnostics and therapeutics.