Nanotechnology: Genesis, Growth and Future Prospects

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Abstract:

The current surge of interest in nanotechnology is partly driven by the miniaturization of devices and new technologies. The history of nanotechnology goes back to many centuries. Advanced experimental tools have opened up new possibilities for studying nanostructures down to the atomic level. Among different nanoparticles, magnetic nanoparticles and their dispersions (ferrofluids) are intensively studied owing to their applications in diverse fields such as magnetic refrigeration, catalysis, cell labeling, contrast agents for magnetic resonance imaging (MRI), cell separation, selective removal of cancer cells and drug delivery. Dispersion of magnetic nanoparticles exhibit several fascinating applications in heat transfer, cation sensing, defect sensors, optical limiters, and biomedicine. Besides they are wonderful model systems to probe molecular interactions and structural transitions under external stimulus.

1. Introduction

The seeds of nanotechnology was planted by the physicist and Nobel laureate Richard Feynman in his 1959'[1]. Nanotechnology deals with control and manipulation of matter at the level of about 1 to 100 nm. By now it is well established that nanotechnology can produce smaller, cheaper, faster, better information and devices/systems. The history of nanotechnology goes back to many centuries. For example, gold nanoparticles were used in coloring glasses in medieval times and during the days of ancient Romans and Michael Faraday made gold nanoparticles in1850. So though nanoscience is very new, the technology is very old. The current surge of interest in nanotechnology is partly driven by miniaturization of devices and new technologies. Advanced experimental tools have opened up new possibilities for studying nanostructures down to atomic level. In 2000, national nanotechnology initiative was launched in

US with an approved budget of $500 million. Subsequently, other countries launched similar initiatives to promote the Nanotechnology program. The top five organizations with maximum number of patents on nanotechnology (1970 – 2011) are Samsung Electronics, Nippon Steel, IBM, Toshiba and Cannon. Nanomaterials exhibit peculiar size dependent optical, electrical, magnetic and chemical properties due to (i) the large fraction of surface atoms; (ii) spatial confinement (iii) high surface energy; and (iv) reduced imperfections [2]. Some of the novel properties of nanomaterials over their bulk counterparts are:

- Significantly lower melting point or phase transition temperature due to large fraction of surface atoms.
- Better mechanical properties such as yield strength and hardness.
- Unusual optical properties, magnetic, electronic properties and thermal properties
- High chemical reactivity.

Nanomaterials or structures are classified as 0D, 1D and 2D based on the number of dimensions that are confined to the nanoscale. OD materials are nanosized particles that have their diameters within the nanometer range (e.g., nanoparticles), 1D materials have a nanometric diameter but have a length that is much larger than nanoscale, 2D materials have a thickness in nanoscale but have larger in the other two dimensional planes (thin films). 3D materials have length scale larger than nanoscale in all three dimensions. Among different nanoparticles, magnetic nanoparticles and their dispersions (ferrofluids) are intensively studied owing to their applications in diverse fields such as magnetic refrigeration, catalysis, cell labeling, contrast agents for magnetic resonance imaging (MRI), cell separation, selective removal of cancer cells and drug delivery.[3] Another class of materials which is becoming popular in these days is smart materials or stimuli responsive materials. These are material with an ability to change their properties under a stimulus like, heat, temperature, sunlight, pH, stress, strain , magnetic or electric field etc.

Nanostructures have been present in nature for millions of years (e.g., moth's eye, coccolith, alpine flower, butterfly, gecko, lotus leaf). Now scientists and engineers are trying to create such nanostructure by learning from nature. The unusual properties of nanomaterials have been employed in a variety of applications such as solar cell designs, biomedical applications, light emitting diodes, lasers, photography, catalysis, biological labeling, photonics, optoelectronics, information storage, catalysis, nanoelectronics, electric batteries, field emitters, radiation sources, spintronics, sensors, field emission displays, gas sensors, quantum computing, energy storage, energy conversion devices, and hydrogen storage media. What we see today is the evolutionary application where we improve the existing processes, materials and applications by exploiting the unique size dependent properties of materials at the nanoscale. A good example for this is the computer/electronics devices where nanolithography made interconnects with smaller nanostructure that enabled to shrink the size of electronic devices and computers.

2. Work Done at IGCAR

Dispersion of magnetic nanoparticles exhibit several fascinating applications. Besides they are wonderful model systems to probe molecular interactions, structural transitions under external stimulus etc. In this section, I discuss a few applications developed in our laboratory using magnetic nanofluids.

2.1 Nanofluid with tunable thermal properties

In 2008, we experimentally demonstrated the tunable thermal property of a magnetically polarizable nanofluids for the first time.[4] By controlling the linear aggregation length, the thermal conductivity (TC) was enhanced up to 300 % with a small fraction of particles. **Figure 1** shows the thermal conducitivity ratio and the enhancement as a function applied magnetic field in the magnetic nanofluid containing 4.5 vol.% of Fe_3O_4 nanoparticles.

This discovery enabled new possibilities to use magnetic nanofluids as a new class of coolants for nanoelectromechanical system and microelectromechanical system based devices. .[5]

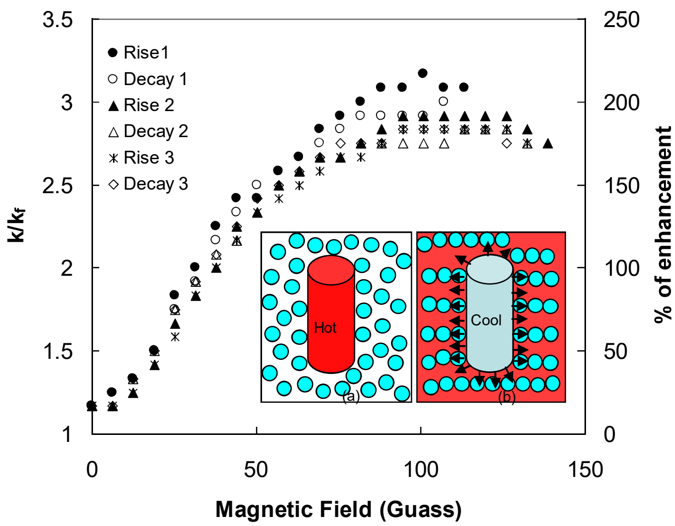

Figure 1. The thermal conductivity ratio and the enhancement as a function applied magnetic field. The inset shows the mechanism of heat transport from a cylindrical device immersed in magnetic nanofluid without and with magnetic field.(Reproduced from J. Philip et al. Appl. Phys. Lett. 92, 043108, 2008).

2.2 Nanofluid based optical sensor for defects detection.

We have developed a simple sensor for detecting internal defects in materials using a magnetically polarizable nanoemulsion. This new technique enabled visual inspection of buried defects in ferromagnetic components and has many advantages over the conventional magnetic flux leakage testing probes. **Fig. 2 a-i** show the schematics and the corresponding photographic images of the nanofluid sensor response.

The centre line on the colour pattern was straight for the rectangular slot and semicircular pattern for the cylindrical slot. The defects are clearly discernible from the images, though color contrasts were not very clear.[6]

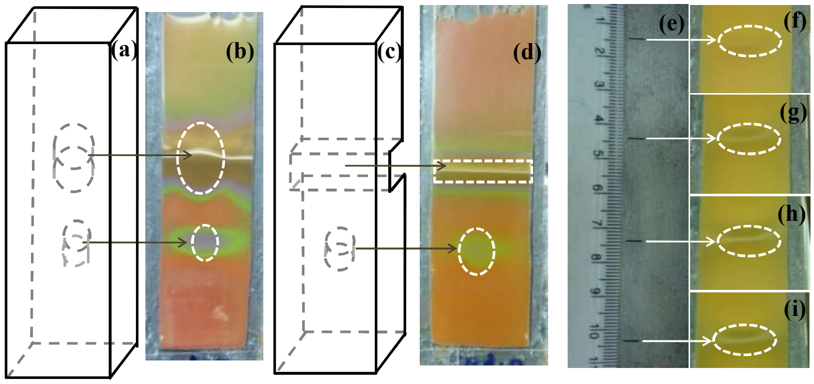

Figure 2. Schematics of the specimens S1–S3a–d (a, c and e) and the corresponding photographic images of nanofluid sensor (b, d and f–i), respectively. (f–i) are S3a, S3b, S3c, S3d, respectively. [Reproduced from V. Mahendran and J. Philip, NDT&E Int. **60**, 100, 2013)].

2.3 Magnetic nanofluid based sensor for ultrasensitive detection of Analytes:

We have also developed a magnetic nanofluid based sensor for ultrasensitive detection of biologically important metal ions such as Na^+, K^+, Ca^{2+} , Cu^{2+} and Fe^{3+} ions using an oil-in-water nanoemulsions. The sensor was tested for Na^+, K^+, Ca^{2+} , Cu^{2+} and Fe^{3+} ions. This approach is also extended for detection of glucose, ammonia and methanol. **Figure 3** shows the effect of methanol on the Bragg peak.[7]

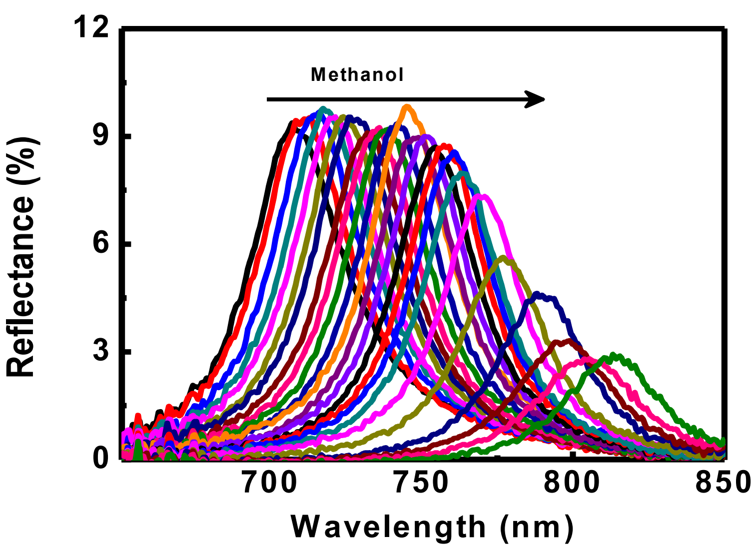

Figure 3. Effect of methanol on the Bragg peak. The arrow indicates the increase in methanol concentration starting from 0 to 5000 ppm. [Reproduced from V Mahendran and J. Philip, Langmuir **29**, 4252 (2013)].

2.4 Magnetic nanofluid based non-enzymatic sensor for urea detection

Using magnetic nanoemulsion, we have developed an optical probe for the detection of urea. In the presence of urea, the probe showed a large wavelength shift in the visible wavelength range, due to complexation of urea with the functional moieties. The fast response time of the sensor and the wide urea detection capability are the unique features of the new sensor.[8]

2.5 Efficient removal of dye using Fe_3O_4 nanofluids:

We have synthesized cellulose capped magnetite nanoparticles for efficient removal of cationic dye. Fig 4. Shows the photograph of methylene blue mixed with magnetic

nanoparticles before and after dye removal. (Bottom figure shows the schematic showing MB captured by magnetic nanoparticles. This new approach enabled a new platform for efficient magnetic separation technology.[9]

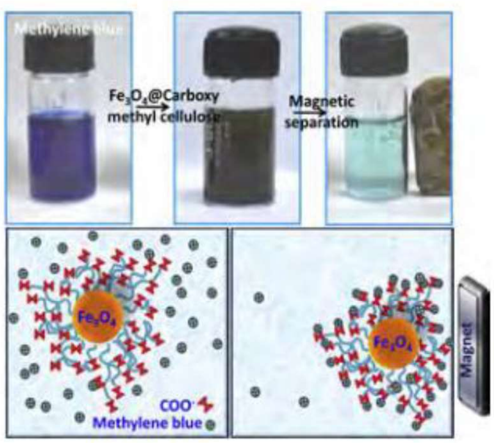

Fig 4. (Top) Photograph of methylene blue, MB mixed with magnetic nanoparticles before and after dye removal. (Bottom) schematic showing MB captured by magnetic nanoparticles.[reproduced from C. Anushree, J. Philip, Colloids and Surfaces A 567 (2019) 193–204)]

2.6 Efficient cancer therapy using magnetic nanofluids:

Magnetic fluid hyperthermia is an emerging cancer therapy where superparamagnetic Fe3O4 magnetic nanoparticles are used to selectively ablate the cancer cells. The advantages of using magnetic nanoparticles include biocompatibility, the distal guidance, superior in vivo efficiency and low side effects. We have developed magnetic nanomaterials with superior heating efficiency by controlling the size and distribution, morphology and insitu orientation of magnetic nanoparticles during the radiofrequency induced heating. Recently we have demonstrated a 62% enhancement in heating efficiency in a magnetic fluid containing SPM particles.[10]

3. Conclusions

Materials with superior properties are necessary for miniaturization, reduction in manufacturing cost and power saving. Among various new materials, nanomaterials have been at the forefront because of their superior properties and interesting technological applications in diverse fields. Nanotechnology has made tremendous progress in various fields over the last two decades. Nanotechnology has become a part of daily life with many nanotechnology products available in market now. Truly revolutionary nanotechnology envisages nanorobots and nanomedicine performing diagnosis, surgery and drug delivery, which are yet to emerge. We have developed several fascinating applications using magnetic fluids in heat transfer, cation sensing, defect sensors, optical limiters and biomedical applications.

References

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Biosketch of Dr. John Philip

Dr.John Philip obtained a Ph.D from the Indian Institute of Technology, Madras. He did postdoctoral research at CNRS, France and at University of Hull, UK. In 1995, he joined the Metallurgy and Materials Group of Indira Gandhi Centre for Atomic Research, Kalpakkam. Presently, he is the Associate Director of the Materials Characterization Group and Head of Smarts materials section at the metallurgy and materials group. He is also a Professor at Homi Bhabha National Institute. He is an elected Fellow of the National Academy of Sciences.

He has six patents in his credit and over 300 publications in leading refereed international journals. His H-index is 57 with over 15000 citations. He has delivered more than 180 invited lectures in India and abroad. His name is listed in World's top 2% scientists data published by Elsevier and Stanford University, USA in the years 2019, 2020 and 2022.

He is the recipient of several awards, which include Science and Technology excellence award, INS medal, NDT man of the year award, MRSI medal and Ron Halmshaw award of British Institute of NDT and Distinguished Faculty award of HBNI in 2015 and Homi Bhabha Science and Technology award in 2016. He was the founding editor-in-chief of the Journal of Nanofluids of American Scientific Publishers and served as EIC for 8 years. He is an editorial board member of journals and reviewer of many international journals and national and international funding agencies. He is a research council member of ARCI, DST, Hyderabad, Member, Scientific Advisory Committee of DST, academic council member of Hindustan university, and medical Biotechnology and nano-technology sectional committee of Bureau of Indian standards. 21 Ph.D students have completed their Ph.D under his guidance.