Condensed matter and materials science—and CSIR

A. V. Narlikar
National Physical Laboratory, Dr K. S. Krishnan Road, New Delhi 110012, India

Much will be missing still,
And much will be amiss.

– Abraham Cowlwy
(1618–1667)

The progress in condensed matter and materials science in the CSIR network of laboratories is briefly traced and the highlights of the current status and of recent R & D efforts are described. Attention is drawn to some of the challenging areas of frontal research.

Right since its inception in 1942, the CSIR has been sufficiently flexible in its approach of promoting scientific and technical research in the country. Broadly, its mainstay has been to exploit indigenous expertise and resources in a substantial way to meet the present and futuristic needs of technologies and industries in the country.

CSIR has always encouraged the pursuit of relevant basic research. Indeed, to quote M. G. K. Menon, the former Director General and subsequently the Vice-President of CSIR, 'I have very often emphasized that in the case of CSIR, the word "scientific" precedes the word "industrial"; and in fact the organization can be effective for industrial research only by carrying out scientific research'.

It is in this perspective that condensed matter and materials science have evolved in the family of CSIR laboratories. A striking manifestation of this is that the work on soft ferrites at NPL, during mid 1950s to late 1960s led to the Central Electronics Ltd, a public sector undertaking which emerged out of NPL in early 1970s.

Materials science in CSIR network

CSIR comprises a vast network of 38 laboratories, spread from Kashmir to Kerala, and Rajasthan to Assam. Also, materials science is a broad discipline, and possibly every laboratory in the CSIR family may have materials-related activity in some form or the other, all of which cannot be reviewed in the present paper. An attempt is made to highlight at least some of the efforts of the laboratories having materials science as a prominent activity. Finally, progress made in respect of industrial processes and various devices developed, which in the accepted sense are considered beyond the purview of materials science, is not considered in this paper.

In what follows, we briefly present the highlights, giving

- Progress and status of condensed matter in CSIR
- Progress and status of materials science in CSIR
- Future challenges.

Condensed matter

(i) *Foresight and vision of Prof. K. S. Krishnan, NPL (1950–61).* Until 1950, solid state physics had mostly been ignored in the country. Majority of research in experimental physics in various universities and few of the research institutes were primarily confined to optical studies, spectroscopy and X-ray crystallography. Realizing the growing importance of solid states physics, K. S. Krishnan, the Founder Director of NPL, provided a significant impetus to the field. In particular,

- In 1952, low temperature physics division was started with the help of David Shoenberg of Cambridge University (UK),
- Full fledged helium liquefier system, first in the country, was installed in 1953,
- 3.2 T Electromagnet was procured for frontal experiments.

As a result, in early 1950s, NPL became a unique place for frontal studies of low temperature properties of solids.

(ii) *Highlights during Krishnan days (1950–61).* One of the early measurements of de Haas van Alphen effect on Bi and Zn were made at NPL (Dhillon and Shoenberg *Philos. Trans. R. Soc.*, 1955, **A248**, 1). Susceptibility of paramagnetic salts was also extensively investigated. Measurements of low temperature specific heat and thermal expansion of solids were carried out. This apart, Krishnan and his collaborators (S. C. Jain, S. K. Roy, R. Sundaram) published several papers in *Nature* and *Proceedings of the Royal Society* on:

- Elastic constants of alkali halides,
- Thermionic constants of metals and semiconductors,
- Temperature distribution in electrically heated metallic rods and tubes.

Krishnan was much concerned with the 'relevance' of the above basic research for technical applications, as is evident from his following observation: 'Such detailed information apart from its intrinsic interest, will also be helpful in connection with the design of sealed in heating elements, such as are used for thermionic or illumination purposes.'

(iii) *Condensed matter studies during 1961–87.* During this period, apart from NPL, noteworthy work was being done in other CSIR laboratories, particularly NAL and NCL. High pressure physics was actively pursued at NAL while novel mechanisms for superconductivity, even high temperature superconductivity, were under active consideration by theorists at NCL. It is worth pointing out that during 1967–70 the phenomenon of photo-induced superconductivity was theoretically envisaged for the first time at NCL, and it is exciting to note that only about two years back such a phenomenon is experimentally found true for certain cuprate systems. Since then, this has become a frontal area of considerable topical interest. Table 1 lists various areas of condensed matter physics being actively pursued during 1961 to 1987.

(iv) *Condensed matter studies, 1987–to present date.* With the advent of high temperature superconductors in 1987, the emphasis of condensed matter research at NPL was shifted to the new materials, i.e. different types of cuprates. Both theoretical and experimental studies are in active pursuit to understand high T_c phenomenon. Heavy fermion systems are also receiving intensive theoretical attention. Since 1991, expertise has been developed in the use of nano-probe techniques which have been effectively used to gain insight into cuprates and other novel systems. Some of the highlights of the theory and experimental groups of condensed matter are depicted in Tables 2–4.

These apart, some of the sophisticated facilities developed at NPL, such as double, triple and quadruple crystal X-ray diffractometry have been yielding new insights into challenging condensed matter problems. Such studies on natural diamond crystals have enabled first time direct observation of forward diffracted beam and anomalous transmission of X-rays (Borrmann effect) even for thin crystals with varying state of perfection.

Materials science

A wide range of expertise and specialized facilities existing in various CSIR laboratories are being effectively utilized to meet the frontal challenges posed by a host of new materials which include building materials, carbon materials, different types of composite systems, advanced ceramics for structural and electronic applications, alloys with special properties, a wide variety of polymers, a range of optical, photoconducting, phosphor materials, solar cell panels, standard reference materials for trace

Table 1. Areas of condensed matter actively pursued during 1961–87

NAL	High pressure physics (1967–79)
NCL	Superconductivity theory Photoinduced superconductivity (1967–70)
NPL	Low temperature transport studies; Kondo systems Mössbauer spectroscopy of ferroelectrics Lang topography of crystal defects and high resolution X-ray difractometry Josephson tunnelling, nonequilibrium superconductivity A-15 superconductors; their formation and ordering; ESR studies Superconductors containing magnetic elements Heavy fermion systems: low temperature transport studies Theoretical work on quasi-one dimensional conductors

Table 2. Condensed matter theory (1987–present date)

Considering the low carrier density and Coulomb interaction in cuprates and using excitonic model, where excitons form due to inter-band transitions between bands, it has been found that band states are coupled coherently so that energy and momentum of the electronic states become nondefinite with the result that the R–T behaviour turns linear and gap vanishes (Lal and Joshi, *Phys. Rev.* 1991, **B43**, 6155; 1992, **45**, 361.

Above calculations have been extended to explain photoemission, tunnelling and NMR data of superconducting and normal states. Approach has been compared with RVB and some obvious drawbacks of the latter are indicated (Lal and Joshi, *SSC*, 1992, **83**, 209).

An exciton-based model has been considered for superconductivity in doped fullerenes (Lal and Joshi, *SSC*, 1991).

A new variational approach to electron correlation has been proposed which is found very suitable for applications to strongly correlated systems like heavy fermions.

Table 3. Condensed matter (experimental) High T_c superconductivity (1987–present date)

Important results obtained during early 1987 (i) Unstable extra high T_c and (ii) weak-link nature and (iii) drastic reduction in T_c of Y-123 upon Zn substitution (for Cu) (Jayaram *et al.*, *Phys. Rev.* 1988, **B38**, 2903).

Focus of the work has been substituted systems of 2-1-4, 1-2-3, 1-2-4, Bi (Tl)-2122/-2223. Role of in-plane and out-of-plane disorder has been recognized through host of studies like sp. heat, resistivity, susceptibility, etc. Out-of-plane disorder seems to make systems more 2D and exhibit fluctuations (Lal *et al.*, *Phys. Rev.*, March/April, 1994)

Pressure studies on 1-2-4 system have revealed transformation to 1-2-3 (*ortho*) and 1-2-3 (*tetra*) (B. P. Singh *et al.*, *Phys. Rev.*, 1992, **B46**, 3573).

Superconductivity, localization and VRH, etc., have been investigated in La-214, Bi-2122, Y-124 systems doped with Fe, Zn, Eu, Dy, Tm, Pr, Ce (Awana *et al*, *Phys. Rev.*, 1993, **B48**, 1211)

In Bi- (and Tl-) cuprates, results indicate both metallic type hole conduction of Cu-O planes and semiconductor-like electron conduction of Bi-O planes to be important. A two band model seems to explain the thermopower behaviour reasonably well. Also, these features seem to prohibit any universal relationship between T_c and carrier density (Awana *et al*, *Phys Rev Lett.*, 1993, **71**, 303, *Phys Rev B*, March, 94) analysis, etc. These programmes of different CSIR laboratories are listed in Table 5. The efforts of various laboratories are in general not duplicative but are mostly complimentary and collaborative.

(i) *Building materials.* This is an important area having prospects of large scale utilization. The efforts are primarily directed to find a viable substitute for wood, using natural or synthetic fibres, or industrial and agro-wastes, etc., and also to fabricate special kinds of bricks, tiles, roofing and other similar materials with low costs and improved features. Progress made on this area is briefly summarized in Table 6.

(ii) *Carbon materials.* Various types of materials based on carbon are being fabricated and studied at NPL. These include glassy carbon, flexible carbon sheets and high density–high strength–isotropic graphite, as depicted in Table 7.

Apart from above, the NPL group has developed the fire-resistant PANEX fibres which are used for flame proof clothing. They are synthesized by low temperature thermal stabilization of PAN fibres. These materials also find uses as a filter in carbon–carbon composites such as used for aircraft brake linings. Special kind of pitches namely, performing pitch and impregnating pitch which find use in carbon–carbon composites have also been developed. Impregnating type of coaltar pitches are extensively used in densification of large graphite electrodes used in steel making. The above group, in addition has developed activated carbon fibres which find major application in the separation, purification, pollution control and recovery of organic vapours. The material fabricated is highly porous having predominantly micropores and shows high rate of adsorption and is inert to acidic and alkaline media.

Composites

The work on composite materials is being pursued at several laboratories in the CSIR network, particularly at NPL, NAL, NCL, RRLs (Bhopal, Jammu, Thiruvananthapuram). Broadly, these composites may be considered of three types: carbon–carbon composites, synthetic fibre–polymer composites and metal–matrix composites. The strengthening entities that are reinforced in the case of the first two are mostly in the fibre form while in the third they are in the particulate form which essentially makes the metal–matrix a dispersion hardened metal or an alloy. By suitably choosing the matrix and the reinforcing entities the mechanical properties of materials, their density, as well as thermal resistance can be vastly varied. As a result, the composites find an enormous and wide use. Carbon–carbon composites, such as being developed at NPL, for instance, can retain their commendable strength up to temperatures of 3500°C, and owing to their low density they have become an obvious choice for some of the aerospace applications. The weave pattern of the carbon fabric as well as the type

Table 4. Condensed matter (experimental) nanostructural studies (1991–present date)

STM studies corroborate that excess oxygen in Bi-2122 intercalates Bi–O planes and STS reveals the Bi–O layers becoming quasi-insulating. This results in diminished interlayer coupling and decrease in T_c. By nitrogenation T_c can be optimised to 96 K.

Formation of growth spirals in basal plane of HTSC single crystals of 1-2-3, Bi-2122 and psycco have been observed with step heights agreeing with c-parameter.

Intercalation of various organic molecules in Bi-2122 has been investigated.

Molecular lattice of C_{60} fullerene has been investigated (Narlikar *et al.*, *Philos. Trans. R. Soc*, 1994, 346, 307)

Carbon cage of individual C_{60} buckyball has been resolved which shows anomalies and defects in close accord with the predictions of molecular dynamics simulations (Narlikar *et al*, *Proc. R Soc.*, 1994, 444, 325).

Table 5. Materials science programme of CSIR laboratories

Building materials	CBRI, CGCRI, RRLs (Bhopal, Bhubaneswar, Thiruvananthapuram)
Carbon materials	NPL
Composite materials	NAL, NPL, NCL, RRLs (Bhopal, Thiruvananthapuram, Jammu)
Advanced ceramics	CGCRI, NPL, NML, NCL, CEERI, IICT, RRL (Thiruvananthapuram)
Metals and alloys	NML, NPL, NAL, CECRI, RRL (T)
Superhard materials	NPL, NAL
Optical materials, phosphors, photo-conducting solar cell materials, coatings, etc.	NPL, CGCRI, CEERI, CECRI
Standard reference materials	NPL, CBRI, CFTRI, CSMCRI, IICT, IIP, ITRC, NEERI, NGRI, NIO, NML, RRL (Jorhat)

Table 6. Building materials

Two main approaches being followed:	
(i)	Use of natural fibres, minerals and industrial and agro-wastes for improved and cheaper materials.
(ii)	Products based on plastics and polymers for building materials, anti-corrosive treatments for metals and concretes and pollution-free bricks and lime kilns.
CBRI	Examples of technologies transferred are: semi-mechanized brick making machine, fly ash bricks
CGCRI	Hollow bricks, glazed tiles and bricks, roofing panels, glass reinforced gypsum composite—A substitute for timber.
RRL (Bhopal)	A combination of red mud and sisal fibres in polymer matrix as alternate material for doors, door panels. 3 mm thick material compares well in strength with 10 mm ply
RRL (T)	Natural fibre-polyester composites; coconut coirs, banana fibres, etc. hold promise.

of fibres that are used and the processing conditions followed, all have significant effect on the mechanical performance of the material. Similarly, aramid and carbon fibres in polyester and epoxy resins, as fabricated at NAL, NCL and RRL(J) have found useful applications as engine components of two wheelers, locos and military and civil aircrafts. Amongst metal matrix composites, Al–Mg, Al–Cu and Al–Li are being strengthened by dispersion of SiC, graphite, mica, zircon as well as by synthetic fibres (NPL, NAL, RRL(B)). Table 8 provides a summary of the status of these materials.

Advanced ceramics

These are one of the earliest materials investigated in the CSIR laboratories. The development of soft ferrites like (Mn, Zn) and (Ni, Zn) for components of radio industry, during 1960s at NPL led to the formation of the CEL during early 1970s. Similarly, the work carried out on ferro and piezoelectric ceramics in late 1950s at NPL resulted in setting up of a pilot plant at BEL in collaboration with NPL which has since then bloomed into a large production centre for electronic components of radio and television industry. Work on advanced ceramics, which include structural, magnetic, ferro and piezoelectric, conducting and superconducting ceramics is being pursued at several CSIR laboratories, namely CGCRI, NPL, NCL, NML, IICT, CEERI, RRL(T), as shown in Table 9.

Metals, alloys and superhard materials

These include various low carbon ferro alloys, steels formed with Mn, and light weight Al–Li alloys (see Table 10). The table also lists the work on diamond and cubic boron nitride (CBN) which are the materials of superhard category.

Polymers

Polymers are in focus at NCL and also at other CSIR laboratories such as NPL and CECRI, as shown in Table 11. There exists a considerable interest in conducting polymers and to use their Langmuir–Blodgett films for devices.

Optical materials, phosphors, optical and photoconducting coatings and films

As shown in Table 12, there are several laboratories of the CSIR contributing to this wide category of materials that includes a range of optical glasses, multilayer coatings, phosphors for different applications, photocon-

Table 7. Carbon materials

NPL

(i) Glassy carbon: A very low porosity form of carbon with characteristics of both glass and industrial carbon. *Applications.* Crucibles, substrate heater, bio-medical (dental implants, heart valves).
Synthesis. By controlled carbonization up to 1000°C of phenol formaldehyde resin precursor.

(ii) Flexible graphite sheets—substitute for asbestos. *Applications.* Sealing of gaskets and packings, lining for crucibles and casting moulds, heat shields, electrode for high energy density battery, etc.
Synthesis. By exfoliation of graphite which results in highly puffed-up material which when compressed gives a flexible sheet.

(iii) High density–high strength–isotropic (HD-HS-IG) graphite: *Applications.* Graphite electrodes, brushes, contacts, crucibles, seals, bearings, hot pressing dies, nuclear graphite, rocket nozzle, etc.
Synthesis. From liquid crystalline mesophase, spherules (5 to 15 μm) formed in suitable coal tar pitches by heat treatments. These mesocarbon microbeads (MCMB) are separated out by solvent extraction and then hot moulded into plates and carbonized, 2700°C

Table 8. Composites [NPL, NAL, NCL, RRL (B), RRL (J), RRL (T)]

Carbon–carbon composites

Light weight, high specific heat, low thermal expansion, low ablation and erosion at high temp., and retain their high strength up to 3500°C. Ideal for aerospace and military applications, e.g. reentry nose tip, heat shield, fighter brake pads, nozzle throat and exit cone. Whole process comprises a technology package with subsystems: (1) carbon matrix precursor, (2) carbon fibre multidirectional weaving process, (3) densification and (4) ceramic coating for protection against high temp. oxidation.

PAN (Poly–Acrylo–Nitrile) based carbon fibres having multidirectional weaving in 3D preform are used along with a pitch or thermosetting resin matrix precursor. Green composite is carbonized several times at 1000°C after repeated high pressure impregnations before final graphitization treatment at 2700°C. Protective coatings developed are based on borates, phosphates, SiC, etc.

Synthetic fibre–polymer composites

Synthetic fibres
Glass, aramid (aromatic polyamide) (Kelvar-49, Dupont) and carbon.
Aramid prepared at NAL (NALAR fibres).
Carbon fibres (NPL).

Matrix resins. Polyester and epoxy.
Polyester. General purpose, flame retardant, chemical resistant, high temperature purpose.
Epoxy. Resins (DGEBA and NOVOLAC) are for high temperature. Elastomers are added to improve ductility.

NCL	Fibre reinforced thermoplastic for critical engine components of two wheelers.
NAL	Carbon fibre reinforced plastic rudder for military and civil aircrafts.
RRL (J)	Fibre reinforced plastic gear castings for 2600 HP locos.

Metal–matrix composites

NPL [with DMRL and RRL (T)]	Al alloys reinforced by SiC in particulate form (different particle sizes and fractions).
NAL	Fibre reinforced Al Li laminates for aerospace.
RRL (B)	Al alloys reinforced with graphite, mica, talc and zircon have wear resistant characteristics

Table 9. Advanced ceramics

(I). For structural and engineering applications	
CGCRI	(i) Reaction bonded silicon nitride (RBSN) (for turbocharge rotors)
	(ii) Nitride bonded SiC (low creep material)
	(iii) Dense silicon nitride by liquid phase sintering (for diesel engines, turbine, cutting tools, etc.)
	(iv) Sialons (solid solution of silicon nitride and alumina) (for making cutting tools). A low creep material.
(II). Ceramics for electronic and electrical applications	
(A) Magnetic ferrites	
NPL	(i) Mn–Zn ferrites (for POT cores, RF cores etc.)
	(ii) Ni–Zn ferrites (for fre. range: 1–25 MHz)
NPL, NCL, NML	(iii) Hard ferrites. Ba and Sr ferrites
IICT.	Mn–Mg and Li ferrites (for microwave applications)
NPL, NCL, NAL	Gamma iron oxide, chromium dioxide powders for magnetic tapes
(B) Ferroelectric and piezoelectric ceramics	
NPL.	Ceramics based on TiO_2 and $BaTiO_3$ (for resonant circuits with low loss).
NPL, NCL	Range of PZT ceramics doped with La, Fe, Cr etc. (for ultrasonic cleaner, high power transducer devices, low power transducers and gas igniters, sensitive receivers, filters and resonators)
(C) Conducting and superconducting ceramics	
NPL, NCL	Varistors based on zinc oxide mixed with Bi_2O_3, MnO, NiO, SiO_2 Thermistors based on manganates Beta alumina tubes with zirconia toughening NASICON (sodium–zirconium–silicon phosphate)
NPL, NCL, CGCRI, CEERI, RRL (T)	High T_c cuprate superconductors, g. La 214, Y(Re)123, Bi-2122, etc., collaboration led to working model of SQUID.

Table 10. Metals and alloys

NML	New grades of manganese-containing steels for high temperature use. Low carbon ferro alloys. Fe–Mo, Fe–W, Fe–V, Fe–Mn and Fe–Cr. (good toughness, low ductile–brittle transition temperature).
NPL (with HAL)	Al–Li alloys for aerospace use.
Superhard materials (NPL, NAL)	
NPL	At NPL 200 tonne cubic press is being used to synthesize (i)diamond and (ii) cubic boron nitride. Boron nitride crystals For diamond starting material is graphite and nickel, invar and monel as catalyst solvents. For CBN, starting material is hexagonal boron nitride (1800°C and pressure of 68 kb).

ducting films, photovoltaic materials, solar cell panels, DLC films, etc.

Standard reference materials

Standard reference materials are needed for precise measurement of major and minor constituents of different materials and are in frequent demand in industrial quality assurance programme of different manufactured goods. They are required for calibration of different analytical instruments and for testing the validity of different analytical methods in the area of environment, electronics, medical, agricultural sectors, etc. With NPL as the nodal laboratory, a programme of preparing a range of standard reference materials has been undertaken in collaboration with a number of CSIR laboratories and its present status is indicated in Table 13.

Conclusions

To sum up, it is clear from a wide range of materials being produced and studied within the CSIR network that the laboratories, by and large, are well equipped in terms of available expertise and sophisticated infrastructure to meet any future challenges that may be posed by new excitements, both in condensed matter studies and in respect of host of materials currently under investigation. At the same time there is an undeniable need to have various materials developed todate fully exploited for numerous applications for which they are supposed to be best suited. Although many of the materials fabricated in the CSIR laboratories are in demand of both public and private sector industries, one always wishes to have a greater response for more recent materials. Clearly, this necessitates creation of more awareness and confidence for the new materials among potential users, which could be manufacturers, engineers, medical doctors, etc. Indeed, it is in this background that Marketing Cells have been opened recently in the CSIR network.

Despite a rather extensive list of important materials being developed in the CSIR laboratories, presented above, one may mention some of the potential materials areas needing attention. Two most obvious ones are (i) photonic materials, and (ii) materials for health care technology.

Future challenge: Nano-regions

With the advent of various nanoprobe techniques, now commercially available since last four to five years, such as scanning tunnelling microscopy (STM), atom force microscopy (AFM), and magnetic force microscopy

Table 11. Polymers

NCL	Synthesis and studies of variety of polymers, development of 'Jalshakti', a water absorbing polymer with relevance to wasteland development, forestry and edible oil programmes of the country.
NPL, CECRI	Conducting polymers At NPL, a number of conducting polymers such as poly(o-toluidine), poly(ethylaniline), poly-*n*(phenyl aniline), poly-*n*(phenylenevinylene) have been synthesized and characterized. Their composites in nylon matrix have also been fabricated.
NPL, NCL	Deposition and characterization of ordered Langmuir–Blodgett (LB) films of conducting polymers for device applications are in progress

Table 12. Optical materials, phosphors; optical and photoconducting coatings; and films (CGCRI, NPL, CEERI, CECRI)

CGCRI	Twenty seven varieties of optical glasses and radiation shielding window glasses for attenuation of high energy radiation in nuclear reactors. Nd-doped laser glass for use in range finders. Silicate laser glass for use in plasma applications. Laser glass discs and rods for defence.
NPL, CGCRI	Multilayer coatings for beam splitters, anti-reflection coatings, interference filters, etc. for space applications.
NPL, CECRI	Phosphors
NPL	Phosphors for X-ray screens (Gd–O–S:Tb) for colour TV tubes (Y–O–S.Eu) Electroluminescent (green): ZnS:Cu, (yellow): ZnS Cu,Mn.
NPL, CECRI, CEERI	Photoconducting films, photovoltaic materials, solar cell panels
CECRI	Electrochemical approach for synthesis of CdS, CdSe, CdSeTe, CdTe, GaAs, CdZnS, etc. (pulse plating technique)
NPL	aSi H, aSiG H, etc. (asymmetric plasma CVD)
NPL	DLC films

(MFM), a whole new challenging world of nano-regions with the atomic level resolution has come at the forefronts to become an area of great topical interest. These techniques are being increasingly used by physicists, chemists, materials scientists, device engineers, and even by molecular biologists and medical researchers for varied purposes. Majority of frontal problems associated with all kinds of materials have now come to a stage where a more prominent leap in their understanding is anticipated only by extending studies of nano-regions, which has made the above nanoprobes exceptionally important and crucial.

Table 13. Standard reference materials: (Bhartiya Nirdeshak Dravyas) [NPL, CBRI, CFTRI, CSMCRI, IICT, IIP, ITRC, NEERI, NGRI, NIO, NML, RRL (JORHAT)]

Materials already available at NPL	
BND 101.02 Pb	Concentration 1.04 (0.03 ppm)
BND 102.02 Pb	Concentration 2.08 (0.02 ppm)
BND 201.02 Cd	Concentration 0.96 (0.02 ppm)
BND 301 As	Concentration 0.99 (0.02 ppm)
BND 401 Cr	Concentration 0.98 (0.02 ppm)
BND 402 Cr	Concentration 1.98 (0.02 ppm)
Materials under preparation	
Se & Hg in high purity water	
Pb, Cd, As, Cr, Hg and Se in high purity water	
High purity nitric acid and hydrochloric acid	
Si powder for diffraction and defect density	

Some of the exciting studies of nano-regions, currently in progress at NPL, pertaining to various frontal materials, such as fullerenes and layered cuprate superconductors, were mentioned in Table 4. The future potential of these techniques may be understood with further illustrations. For instance, the AFM, when operated as a frictional force microscope, serves as a major tribological probe to understand the problem of friction at the atomic level, which during last year or so, has led to a new frontal research area of nanotribology. Similarly, MFM has been effectively used to provide the direct magnetic mapping of the flux distribution of the recording heads. Such direct magnetic mapping is currently going a long way to help electronic industries to design better qualities of recording heads. This technique along with STM also finds exciting use in condensed matter research to study charge density waves, to map Abrikosov's vortex lines in type II superconductors and to explore the transition to the glassy vortex state exhibited by high T_c cuprate superconductors. Apart from serving as local probes of unsurpassed resolution, these technique have started playing a crucial role as tools in the hands of device engineers to fabricate nanodevices, with nanolithography and atomic level doping, which undoubtedly would have the key role in future device technology.

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