GENNESYS
WHITE PAPER

A NEW EUROPEAN PARTNERSHIP
BETWEEN NANOMATERIALS SCIENCE & NANOTECHNOLOGY AND
SYNCHROTRON RADIATION AND NEUTRON FACILITIES
GENNESYS

GRAND EUROPEAN INITIATIVE ON NANOSCIENCE AND NANOTECHNOLOGY USING NEUTRON- AND SYNCHROTRON RADIATION SOURCES
# TABLE OF CONTENTS

## PREFACE

H. Dosch  
Chair of the GENNESYS Initiative; Director Max-Planck-Institut für Metallforschung  
10

## FOREWORDS

### Research

J. Potocnik  
European Commissioner for Research, Brussels (B)  
H. Rohrer  
Former IBM Research Fellow; Nobel Laureate, Zürich (CH)  
F. Fedi  
Milan (I)

### Education

P. Couchevin  
Councillor of the Swiss Federal Council; Head of the Federal Department of Home Affairs (DHA), Bern (CH)  
J. Figel  
European Commissioner for Education, Training and Culture, Brussels (B)

### European Parliament

P. Busquin  
Member of European Parliament, Committee on Industry, External Trade, Research and Energy (ITRE)  
Chairman of the Scientific Technology Options Assessment Panel (STOA)  
Former European Commissioner for Research, Brussels (B)  
J. Buzek  
Member of European Parliament, Committee on Industry, External Trade, Research and Energy (ITRE)  
Rapporteur on the Seventh Framework Programme (FP7) for the European Parliament’s Committee on Industry, External Trade, Research and Energy (ITRE), Brussels (B)

### Industry

R. Iden  
Senior Vice President, BASF S.E.  
Co-Chair of the European Technology Platform for Sustainable Chemistry (ETP SusChem), Ludwigshafen (DE)  
J.C. Lehmann  
Former President and Current Member of the National Academy of Technologies of France (NATF)  
Former Vice President of Research & Development, Saint-Gobain, Paris (F)

### Large Test Facilities

G. Margaritondo  
Vice President for Academic Affairs, Ecole Polytechnique Fédérale de Lausanne (EPFL)  
President of the Council: ‘European Integrating Initiative for Synchrotron Radiation and Free Electron Laser (IA-SFS), Brussels (B)  
J. Wood  
Chief Executive of the Council for the Central Laboratory of Research Councils, Chilton (UK)  
Chairman of the European Strategy Forum on Research Infrastructures, Brussels (B)  
Prof. Imperial College, London (UK)

### International relations

T. Kishi, Tsukuba (JP)  
Representative from the USA
## 1. INTRODUCTION

1.1. What is nanomaterials science and nanotechnology?

1.2. New materials for new technologies

1.3. Future analytical challenges

1.4. The European Synchrotron Radiation and Neutron Centres

1.5. GENNESYS: A new nanomaterials strategy for Europe

## 2. GENERIC CHALLENGES FOR FUNDAMENTAL RESEARCH IN NANOMATERIALS SCIENCE

2.1. Generic challenges for nanomaterials synthesis

2.2. Nanostructures
   2.2.1. Functional interfaces
   2.2.2. Thin films and multilayers
   2.2.3. Nanodots and nanowires

2.3. Nanomaterials phenomena

2.4. Nanomaterials functions

2.5. Nanomaterials modelling

2.6. General conclusions on generic challenges in nanomaterials research - "GENNESYS Science Centres"

## 3. SPECIFIC CHALLENGES FOR NANOMATERIALS DESIGN

3.1. Introduction: Nanomaterials science – structural and functional materials

3.2. Structural nanomaterials
   3.2.1. Nanometallics
   3.2.2. Nanoceramics
   3.2.3. Nanostructured coatings
   3.2.4. Nanostructured polymers and composites
   3.2.5. Recommendations and requirements for synchrotron radiation and neutron sources

3.3. Functional nanomaterials
   3.3.1. Electronic and semiconducting nanomaterials
   3.3.2. Photonic nanomaterials
   3.3.3. Nanomaterials for nanomagnetism and spintronics
   3.3.4. Superconductors
   3.3.5. Carbon nanomaterials
   3.3.6. Dielectric nanomaterials for future Si-based micro- and nanoelectronics
   3.3.7. Conclusions and recommendations
3.4. Nano-life sciences
   3.4.1. From polymers to biological systems: “self-assembly of soft matter”
   3.4.2. Bio-nanomaterials
   3.4.3. Biomimetic nanomaterials

3.5. Polymers: Soft matter for nanoscience and nanotechnology
   3.5.1. Polymers in bulk industrial processing conditions
   3.5.2. Functional polymers
   3.5.3. Structural polymers
   3.5.4. Polymers: nanoscience and nanotechnology: The chain of knowledge
   3.5.5. Block copolymers
   3.5.6. Polymer nanocomposites
   3.5.7. Future priorities in synchrotron and neutrons mediated polymer research
   3.5.8. Conclusions: Actions for polymer nanoscience and nanotechnology

3.6. Metal Hydrides in future technologies – importance of neutron and synchrotron radiation

3.7. Nanodiamonds

3.8. Nanostructured coatings
   3.8.1. Potential nanostructured coating materials
   3.8.2. Coatings manufacturing
   3.8.3. Nanocoatings research needs
   3.8.4. New research strategies exploiting synchrotron radiation and neutron sources

3.9. Molecular, nanoinorganic materials and hydrides

3.10. Nanomechanical engineering and design
   3.10.1. Mechanical integrity of nanoscale materials
   3.10.2. Joining of nanomaterials
   3.10.3. Future role of neutrons and synchrotron radiation facilities

3.11. Nanocorrosion and protection of nanomaterials

3.12. Nanotribology: Nanowear, nano-friction, nano-adhesion, nanolubrication

3.13. Nanjoining and non-destructive testing (NDT)

3.14. Directions for nanomaterials research

4. SPECIFIC CHALLENGES IN NANOMATERIALS TECHNOLOGIES

4.1. Introduction

4.2. Nanotechnology in the semiconductor and photonic industry
   4.2.1. New nanomaterials for electronics and photonics
   4.2.2. Future role of synchrotron radiation and neutron facilities
   4.2.3. GENNESYS European Technology Centre: “Electronic and photonic nanomaterials”

4.3. Health: Bio- and medical application
   4.3.1. Biomaterials in nanotechnology
   4.3.2. Nanomaterials for medical science
   4.3.3. Nanomaterials for dentistry
4.4. Nano-aspects in future food science and technologies
4.4.1. Introduction
4.4.2. Future trends in nanofood research and technology
4.4.3. Role of synchrotron radiation and neutrons mediated research in food science and technology
4.4.4. Conclusions - recommendations

4.5. Transport: Aeronautics and automotive
4.5.1. Introduction
4.5.2. Future trends for nanomaterials applications in aeronautics: aircraft & engine, automotive
4.5.3. Nanomaterials in aircraft and space structures
4.5.4. Nanomaterials for aeroengines
4.5.5. Nanomaterials in automotive technology
4.5.6. The need for neutron and synchrotron x-ray radiation to study aerospace and automotive nanomaterials and components

4.6. Nanomanufacturing: nanometallurgy, nanoceramics- and nanopolymer/composites processing
4.6.1. Nanometallurgy
4.6.2. Manufacturing nanoceramics
4.6.3. Manufacturing nanopolymer and composites

1.7. Nanomaterials for Energy using Synchrotron Radiation and Neutrons
1.7.1. Energy sources
1.7.2. Nanomaterials research for energy technology – an overview
1.7.3. Use of large research facilities for the development of nanomaterials for energy technology
1.7.4. Challenges in the further development of large synchrotron and neutron research facilities for energy technology
1.7.5. European Nanoscience Energy Centre
1.7.6. Conclusions

ADDENDUM:
TYPICAL ENERGY TECHNOLOGIES — NANOMATERIALS – SYNCHROTRON RADIATION AND NEUTRONS

Add 1. Nanostructured photovoltaics

Add 2. Storage
Add 2.1. Accumulators
Add 2.2. Super capacitors
Add 2.3. Nanoscale materials for hydrogen storage

Add 3. Conversion
Add 3.1. Nanoscale catalysts for the processing of fuels
Add 3.2. Industrial gas turbine – protective coatings
Add 3.3. Materials for solar thermoelectric power generation
Add 3.4. Polymer electrolyte membrane (PEM) fuel cells
Add 3.5. Ceramic high-temperature fuel cells or solid oxide fuel cells (SOFCs)
Add 3.6. Gas separation membranes

Add 4. Rational use of energy
Add 4.1. Tailoring of interfaces to manipulate energy carriers
Add 4.2. Study of new phenomena and properties at the nanoscale

Add 5. Nanomaterials in large-scale production: “New cost competitive, reliable, long lifetime”
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8.</td>
<td>Nanomaterials for nuclear technology</td>
</tr>
<tr>
<td>4.8.1.</td>
<td>Nanomaterials for nuclear technology</td>
</tr>
<tr>
<td>4.8.2.</td>
<td>Nanomaterials for fusion technology</td>
</tr>
<tr>
<td>4.10.</td>
<td>Materials for nanomineralogy</td>
</tr>
<tr>
<td>4.11.</td>
<td>Nanoscale materials in the oil and gas, and petrochemical industry</td>
</tr>
<tr>
<td>4.11.1.</td>
<td>Research goals</td>
</tr>
<tr>
<td>4.11.2.</td>
<td>The potential of synchrotron radiation and neutrons</td>
</tr>
<tr>
<td>4.12.</td>
<td>Nanoscale materials for catalysis</td>
</tr>
<tr>
<td>4.12.1.</td>
<td>Introduction</td>
</tr>
<tr>
<td>4.12.2.</td>
<td>Future role for nanocatalyst materials</td>
</tr>
<tr>
<td>4.12.3.</td>
<td>Research roadmap for nanocatalyst materials</td>
</tr>
<tr>
<td>4.12.4.</td>
<td>The key challenges in the development of nanocatalytic materials</td>
</tr>
<tr>
<td>4.12.5.</td>
<td>Importance of nanocatalyst materials for the future of European industry</td>
</tr>
<tr>
<td>4.12.6.</td>
<td>Key recommendation: science centre: catalyst nanomaterials</td>
</tr>
<tr>
<td>4.13.</td>
<td>Nanomaterials for the environment</td>
</tr>
<tr>
<td>4.15.</td>
<td>Nanomaterials for security</td>
</tr>
<tr>
<td>4.16.</td>
<td>General RD&amp;T visions for nanotechnology</td>
</tr>
<tr>
<td>5.</td>
<td>Nanometrology, Standardisation, Instrumentation — Nanomaterials Technology — The Need for Nanometrology Research and Technology</td>
</tr>
<tr>
<td>5.1.</td>
<td>Great challenges for nanoscale metrology, standardisation and instrumentation</td>
</tr>
<tr>
<td>5.2.</td>
<td>Nanomaterials — key challenges for characterisation</td>
</tr>
<tr>
<td>5.3.</td>
<td>Nanotools — key challenges for analytics</td>
</tr>
<tr>
<td>5.4.</td>
<td>Key challenges for synchrotron radiation and neutrons nanometrology</td>
</tr>
<tr>
<td>5.5.</td>
<td>Importance of nanometrology for European society and economy</td>
</tr>
<tr>
<td>5.6.</td>
<td>Conclusions</td>
</tr>
<tr>
<td>5.7.</td>
<td>Recommendations</td>
</tr>
<tr>
<td>5.8.</td>
<td>Institution of a European Centre for Nanometrology</td>
</tr>
</tbody>
</table>
6. THE NEED FOR NANO METROLOGY RESEARCH AND TECHNOLOGY IN EUROPE
6.1. Importance of nanotechnology for industry
6.2. Nanotechnology forecasts
6.3. Needs for industrial research on nanomaterials
6.4. Industrial research at large test facilities
6.5. Synchrotron radiation and neutron techniques for industrial service in nanomaterials technology
6.6. GENNESYS-Industry partnership: “European Technology Centres”

7. FUTURE IMPLICATIONS OF NANO MATERIALS RESEARCH FOR LARGE-SCALE RESEARCH FACILITIES
7.1. Introduction
7.2. Neutron scattering
  7.2.1. Neutron methods and future challenges
  7.2.2. Future challenges for neutron facilities
7.3. Synchrotron radiation
  7.3.1. State of the art
  7.3.2. Future needs
  7.3.3. Nanomaterials science needs for the upgrade of large-scale facilities
7.4. Conclusions: Future role of European synchrotron radiation and neutron facilities for the development of nanomaterials and nanotechnology

8. IMPLICATIONS OF GENNESYS FOR EDUCATION

9. SOCIETY AND NANO MATERIALS SCIENCE AND TECHNOLOGY

10. CONCLUSIONS – RECOMMENDATIONS – FUTURE STRATEGIES AND ACTION PLAN
10.1. Overall conclusions: Barriers and generic challenges
10.2. Recommendations for further research – order of priorities
10.3. Strategy and action plan
  10.3.1. European research programmes
  10.3.2. Large-scale research facilities: Modernisation and nanoadaptation
  10.3.3. Industrial consortia and European industrial platforms
  10.3.4. GENNESYS’ role in European research strategies
  10.3.5. Need for a new nanomaterials organisation in Europe: Mandate and structure
  10.3.6. Centres of excellence – GENNESYS colleges

11. LIST OF AUTHORS, CONTRIBUTORS AND PARTICIPATING INSTITUTIONS

APPENDIX I: GENNESYS meetings, conferences & presentations
3.3. FUNCTIONAL NANOMATERIALS

Functional materials include all types of chemicals, ranging from organic to inorganic, from metallic to covalent, and from molecular to macromolecular species. In devices, the useful form may be a single crystal, a compound, a thin film or a composite. At the basic level, this offers the possibility of the miniaturization of a device, with gains in space saving, lower weight, improved heat dissipation, and so forth.

These smart materials are underpinning the technological developments of the 21st century, and play an increasingly important role in the economy and our daily lives, with applications ranging from the automotive, communications and consumer industry to health care. Their functionality can cover a wide range of physical properties, such as piezoelectric, magnetostrictive and semiconducting materials, as well as chemical properties, such as catalysis, absorption, chemical sensing, and electrochemical behaviour. Moreover, these smart materials can adapt, or respond to their environments (see Fig. 3.3.1).

The trend in functional materials is towards increasingly smaller dimensions. The interaction between the multiple structures in the components, with ensuing complexity, e.g. quantum dots or magnetic patterned arrays, demands novel destruction-free and in-situ analytical techniques which, in the future, have to be provided by the European synchrotron radiation and neutron facilities.

Furthermore, simply by reducing the size of a material to the nanometre scale, even in one only dimension, e.g. in the realisation of an ultrathin layer, its materials properties change. This is due to quantum confinement effects modifying the electronic properties and thus all relevant materials parameters. Technical realisations which exploit this phenomenon are quantum dot lasers, magnetic (GMR) sensors and read out heads and lasers, the ultra-small metal particles in a catalyst. The materials properties of these ultrasmall structures need to be explored, even on the individual basis of a single selected nanoparticle. This can be achieved by using advanced spectroscopic methods, combined with microscopy, which are only available at modern-day synchrotron sources.

Promising applications of nanofunctional materials
The potential uses of nanofunctional materials are:
• **Coatings**: Corrosion and wear-resistant coatings, as well as thermal barrier and thermal gradient coatings. In future, ‘intelligent coatings’ will become important as, e.g. a response to environmental conditions.
• **Composite materials**: Carbon nanomaterials have a range of special electrical, mechanical and thermal properties. As an additive in polymers, ceramics, metals and textiles, these nanocomposites can improve the matrix material in terms of electrical and thermal conductivity or mechanical strength with low nanomaterial loads.
• **Energy-related materials**: A major goal is an efficient reversible hydrogen storage material. Here, novel microporous materials with an extremely high specific surface area or nanoscale complex hydrides with catalytic nanoclusters may offer the possibility to develop storage materials suitable for mobile applications.
• **Nanoelectronics**: Creation of nanoscale circuits, wires and packaging of semiconductors. The goal of industry is to use these components to manufacture a new class of very small and very powerful electronic devices.
• **Sensors**: Sensors based on nanocrystalline materials offer higher sensitivity and faster response times. These features are already being exploited in metal oxide gas sensors. However, the major problem in gas detection is in selectivity and this is not resolved in a single element sensor. Thus, the future will be in multi-element sensors and the use of neural network methodologies for signal analysis.
• **Catalysts and fuel cells**: Carbon nanomaterials enhance the properties of fuel cells. As catalyst support material for precious metals (e.g. platinum), carbon nanomaterials can help to enhance the power density of fuel cells and help to reduce the amount of platinum.

3.3.1. ELECTRONIC AND SEMICONDUCTING NANOMATERIALS
The impact of electronic materials on modern-day society can hardly be overestimated. Electronic technology is embedded in all branches of industry: computing, household appliances, entertainment etc. Especially in the fields of information processing and technology, the drive towards nanoscale electronics is relentless and holds the promise for increasingly smaller and faster devices. Microelectronics is generally recognised as the enabling technology for present and future information systems. However, the craving for information systems with a higher level of capacity is paving the way for the transition from microelectronics to nanoelectronics in the near future. The Semiconductor Industry Association roadmap contains SiGe buffers for strained Si layers and strained Ge on insulator technology from 2003 onwards. By about 2015, these developments in conventional Si technology will be exhausted due to fundamental physical reasons (quantum effects), as well as to material properties (e.g., no reliable oxide barriers can be fabricated with the required thicknesses in the monolayer range). Therefore, alternatives are being intensively studied (see Fig. 3.3.2).
**STATE-OF-THE-ART**

**Si-based electronics**
- Conventional Si-integrated electronics: end of improvements due to Moore's law in sight (2015)
- SiGe technology: well-developed in Europe, e.g., SiGe buffers for strained Si/Ge heterostructures
- Europe is leading in silicon-on-insulator (SOI) technology, e.g., for high-frequency devices

**Si-based electronics**
- New device concepts based on nanostructures developed in research, e.g., quantum dots

**Optoelectronics**
- Europe is behind in optoelectronics, e.g., III-V heterostructures, GaN/AlN structures, II-VI HgCdTe ternary systems, ZnO/InN and ZnSe devices, and GaAlN for blue and UV emitters (see also the section on photonics)

**Organic semiconductors**
- Materials and devices developed on research level

**FUTURE NEEDS AND CHALLENGES**

**Future potential**
- Continuous improvement of Si/SiGe technology
- High-K dielectrics
- Improving concepts for strained Si/Ge layers beyond virtual SiGe substrates, e.g., using quantum dots as defect-free stressors

**Nanoelectronic breakthroughs**
- Organic electronic materials, e.g., for flexible displays, organic diodelets, bioelectronics
- Materials for powerful storage devices
- New fault-tolerant computer architectures compatible to self-organisation
- Spin electronics
- Quantum computing materials & concepts
- From nanotubes and molecular electronics to organic polymers

**Fabrication challenges**
- Control of growth/self-assembly
- Development reliable manufacturing processes (Combination of top-down & bottom-up approach)
- Combination of new and existing materials and technologies
- Full integration in single 'system-on-chip' components
- Development of strain simulation for cross-checking experimental results

**Characterisation challenges**
- Organic dielectrics
- Self-assembled systems
- Sensitivity down to monolayers
- Characterisation of defects, e.g., grain boundaries, dislocations
- Surfaces and interfaces
- Complex alloys

**FUTURE ROLE OF SYNCHROTRON RADIATION AND NEUTRONS SOURCES**

**Synchrotron radiation**
- Non-destructive investigation of heterostructures and buried nanostructures.

**Characterisation of defects, surfaces & interfaces**
- Use of highly focused nanbeams (< 20 nm) for simultaneous real and reciprocal space resolution
- In-situ studies during growth

**In-situ studies during device operation**
- Exploration of fully coherent x-ray beams for the direct reconstruction of real space properties and to study time-correlation properties (in-situ growth, diffusion, self-organisation, degradation)

**Combination of diffraction, imaging, and spectroscopy of nanostructures**
- Dedicated beamtime for series and failure analysis for industrial development

**Neutrons**
- (Needs further evaluation after the availability of intense pulsed neutron beams)

---

The spectrum includes thin films and super lattices, atomically corrugated surfaces, nanostructured atomic clusters, assemblies of molecular materials, and quantum dots. The pursuit of new methods for preparation, synthesis, characterisation, and detailed examination and prediction of the properties of nanomaterials constitutes nanoscience and nanotechnology. Special technological benefits from nanoscience demand the exploitation of novel properties at the nanoscale to functionalities for industrial application. While, for instance, defects in conventional two-dimensional layers are a decisive obstacle for conventional Si technology, with self-assembled nanostructures, defect-free strained SiGe and strained Si can be fabricated. Hence there is a clear need to control the growth of self-assembled nanostructures, and to combine this new "bottom-up" approach with the conventional lithographic structure definition ("top-down"). Apart from the challenge to create new or better materials and ever smaller structures, it might become necessary to invent new fault-tolerant computer architectures, which are compatible with fluctuations in self-organised materials.

The Si-Ge technology is well-developed in Europe. In the field of optoelectronics, however, Japan and US companies are leading. This includes the development of III-V heterostructures employed in optical fibre communication systems, Ga-In-N-As structures for the production of laser diode, II-VI HgCdTe ternary systems for very long wave-length devices, and compounds such as Zn-Cd-S-Se and Zn-S-Se and Ga-Al-N for visible and UV-light emitters.

**Specific challenges for synchrotron radiation and neutron facilities**

In future Si technology, synchrotron radiation and neutron facilities must contribute to solve urgent material problems, in particular with a view to:
- The study of defects in conventional Si-layers;
- The growth of defect-free strained SiGe and strained Si;
- The determination of inhomogeneous strain fields;
- The determination of inhomogeneous chemical composition profiles;
- The study of self-organised semiconductor nanostructures (quantum wells and dots).

In the development of advanced materials, several research needs have been identified:
- Use of Ge instead of Si: this transition will require extensive characterisation work, including the characterisation of the composition and the roughness at the interface with Ge;
- Design of foams of organic dielectrics as low-K oxides: urgent need for in-situ characterisation techniques;
- Development of Ga-N/Al-Ga-N piezomaterial: systematic destruction-free investigations of strain and dislocations;
- Tailored growth of self-assembled monolayers: systematic investigations of structure, coverage, heterogeneity and steric hindrance;
- Development of plastic electronic materials: microscopic study of the effect of grain boundaries.

### 3.3.2. PHOTONIC NANOMATERIALS

One of the most important discoveries in modern optics is the fact that the optical properties of matter are not invariant but controllable. Three methods for their efficient control are known:

1. Dielectric and metallic nanostructures such as photonic crystals and microcavities.
2. Composite nanostructures, metamaterials, with components whose sizes are smaller than the optical wavelength.
3. Quantum confinement of electrons and holes in nanostructures such as quantum dots and quantum wells.

All these technologies are achieved by the self-organisation of nanomaterials and nanofabrication.

Photonic technologies enabled high-speed broadband telecommunication, and revolutionised displays (flat panel displays). Solid state lasers and light-emitting diodes have replaced other light sources, enabling novel optical solutions from car displays to endoscopic surgery. Compared to the US and Japan, Europe is behind in optoelectronic and photonic applications, and a large effect will be required to close this gap. Severe obstacles have to be overcome in the near future in order to further the photonic field and make it market competitive.

A similar breakthrough is expected for short-distance data exchange, e.g. between CPU's and graphics adapters or storage networks, or within local networks. Here, cost-effectiveness will be the decisive factor. So far, no light sources, modulators and detectors can be fabricated at reasonable costs and with the desired degree of integration with electronic devices. It is unclear at the moment, whether hybrid solutions (which are cost-intensive due to packaging effort) or solutions integrated on chip will (ultimately) be the optimum solution.

The following main fields of development can be foreseen (see also Fig. 3.3.3 and 3.3.4):

- III-V materials: GaN (405 nm) high density optical storage;
- GaAs/AlGaAs (880 nm) coupling to plastic optical fibres;
- GaAs/AlGaAs/GaInP (800-1000) pumping rare earth laser;
- InGaAsP (1310 nm) coupling to silica fibres;
- nP/nGaAs (1550 nm) coupling to silica fibres;
- Organic materials: highly flexible, easy in production, low thermal budget compatible with CMOS, hybrid integration to CMOS possible;
- Integration of photonic circuits (driven by telecommunication systems). Up to 10 GBit/s hybrid integration sufficient, for >40 GBit/s monolithic devices required.

---

**State of the Art**

2004

**PHOTONIC NANOMATERIALS**

- Utilisation of electronic coherence in quantum nanostructures
- Design of radiation field & optical properties of materials
- Nanogrowth & nanofabrication
- Sophisticated single dot & molecule spectroscopy

2008

- Photonic crystal (PC)
- Metamaterial
- Microcavity
- Quantum nanostructure

2012

- Novel QED effects
  - Excitonic AB effect
  - Quantum localisation of photon-controlled NOT gate
- Entanglement of remote nanomaterials
- Photonic crystal microchip

2016

**Timeline**

**Challenges**

Applications

- Super continuum light source
- PC fibre-based gas sensor & laser surgical knife
- PC-based micro component & ultrafast optical switch
- QD laser
- QD-based bioimager
- Multi-frequency optical communication

**Breakthrough**

Novel materials, novel applications

Fig 3.3.3: Roadmap highlighting the future research on photonic nanomaterials research.
- Integration of photonic and electronic components, driven by interconnects: intra-building (also automotive and aerospace), intra-backplane (servers, eventually PCs), intra-chip.

In the search for new applications, new material developments based specifically on nanomaterials are required. In principle, two routes are followed; however, so far, these have been only at the basic research level: (i) the production of colloidal nanocrystals with specially designed optical properties, which have then to be incorporated in a lithographically produced device; (ii) the use of epitaxial methods and self-organisation, to directly introduce nanostructures into devices. In the latter approach, very similar prospects and hindrances are met to the ones in nanoelectronics. In turn, major challenges in material design and material characterisation, requiring novel characterisation solutions, will be encountered. These solutions will have to be developed and provided by the synchrotron radiation and neutron facilities. In particular, the interface structure in heterostructures, defects, and chemical composition and strain distribution within and around nanostructures should be considered important issues (see Fig. 3.3.9).

Particular targets areas for future research exploiting synchrotron radiation and neutron facilities are (see also the following roadmaps: Fig. 3.3.3 and Fig. 3.3.4, and Fig. 3.3.5 for a schematic diagramme):

**Manipulation of optical properties of nanomaterials**
- Development of materials with arbitrary optical properties by sub-wavelength structures.

- Antireflection effect of surface nanostructures, and structural colour originating from periodic structures.
- Nanostructured optical materials ("metamaterials") with arbitrary refractive index, permittivity, or permeability.

**Nanooptical circuits**
- The current optical circuits based on planar waveguides are very large compared with the optical wavelength due to the weak light confinement. To dissolve the scale mismatch with the electronic circuits and to realise electronic-photonic integrated circuits, wavelength-sized optical circuits based on photonic crystal waveguides or plasmonic waveguides is of great importance.

**Non-linear optical devices**
- Non-linear optical devices, which control light with light, are required for all-optical logic devices and for ultimate ultrafast optical communication. In addition to the synthesis of optical materials with large non-linearity, the development of optical cavities based on photonic crystals or plasmonics is required for obtaining large electric fields.

**Nanoostructures for ultrasensitive chemical analysis**
- Giant electric field enhancement in photonic crystals or plasmonic crystals is expected to bring us novel methodologies of ultrasensitive chemical analysis. Research on biosensors or establishment of environment analysis processes, which enable us high speed detection of arbitrary molecules in a small volume with very low concentration, is vitally important.

---

**Fig. 3.3.4: Roadmap on the contribution of synchrotron radiation and neutrons towards functional photonic nanomaterials research.**
Exploitation of the quantum nature of photons

- Quantum nature of photons would be brought into use. Entangled photons are indispensable for quantum computation and quantum cryptography. In particular, realisation of strong light-matter interaction, e.g., based on the combination of quantum dots and photonic crystal cavities, is of prime importance. Single-photon sources, which generate non-classical light, would also be utilised as a new class of light sources.

### State-of-the-Art

**Photonic Nanomaterials**
- Photonic crystals (PC)
- Artificial opal
- Colloidal crystal
- Photonic crystal slab
- Photonic crystal fiber
- Diamond structure
- Simple cubic structure

**Metamaterials**
- Plasmonic nanostructure
- Negative index material
- Chiral structure
- Random and fractal structures

**Microstructures**
- Microsphere
- Microdisc
- Microbumps
- Micropyramid
- Photonic crystal cavity

**Quantum Nanostructures**
- Quantum well
- Quantum dot (QD)
- Quantum ring

**Measurements**
- Near field scanning optical microscope (SNOM)
- Single dot spectroscopy

**Unusual Phenomena**
- Photonic bandgap
- Modified Planck’s law
- Purcell effect
- Smith – Purcell radiation
- Classical localisation of photon
- Small group velocity
- Enhancement of:
  - non-linear optical processes
  - stimulated emission
  - optical bistability
- Waveguides with sharp bends
- Super continuum generation
- Super prism
- Super lens
- Negative refraction
- Surface enhanced Raman scattering
- Quantum confinement of exciton & biexciton
- Resonant oscillation
- Strong coupling
- Rebi splitting

### Future Needs and Challenges

**Main Research Activities**

**Fabrication**
- Sophisticated lithography:
  - Electron beam
  - Focused ion beam
  - Ultraviolet & X-ray
- Controlled self-organisation:
  - STM assisted positioning of QDs
  - Vertically coupled QDs
- Anodic oxidation
- Semiconductor nano/molecules
- Quantum double rings
- Remote fabrication in SEM

**Characterisation**
- Further development of:
  - Probe microscopes
  - Single dot spectroscopy
  - Single molecule spectroscopy
  - Single photon spectroscopy
  - Photon correlation
  - Fourier spectroscopy
  - Ultrafast spectroscopy

**Cavity QED**
- Development of high-Q PC cavity
- QD – PC coupled structure
- Quantum gate operation

**Applications**
- Super continuum light source
- PC fibre-based:
  - Gas sensor
  - Laser surgical knife
  - Optical microcircuit
  - Optical microcomponent
  - Ultra-fast optical switch
- QD laser:
  - QD-based biomarker
  - Multi-frequency optical communication

**Novel Phenomena**
- Quantum localisation of photon
- Optical detection of single spin
- Single molecule Raman scattering
- Single photon propagation in PC
- Entanglement of remote QDs
- Exciton Bohr – Aharanov – Bohm effect
- Controlled NOT gate

**Future Role of Synchrotron Radiation and Neutrons**

**Synchrotron Radiation**
- Material characterisation: defects, interfaces, especially for monolithic integration
- Organic materials development: stability in time-resolved studies, dependence of stability on structure
- In-situ growth monitoring to understand growth phenomena and improve growth techniques
- In-situ device testing, change of properties and degradation of devices during operation, needs non-destructive technique

**Neutrons**
- Systematic neutron studies of electron-phonon interactions to reveal the dephasing mechanism in quantum nanostructures
- Quantum “optics” of neutrons

![Fig. 3.35 Opportunities for synchrotron radiation and neutron techniques in the field of photonic nanomaterials.](image-url)
The ever increasing need to store and process data has fuelled applied and fundamental research in probing the temporal and spatial limits of magnetic switching. Exploring the magnetisation in NiMnSb by applied magnetic field pulses is a very active research field involving real-time studies of synchrotron based time-resolved spectroscopy. Novel switching phenomena based on angular momentum transfer from a spin-polarised electrical current are beginning to be explored. A completely new field is being developed where information transfer is no longer based on charge transport leading to heat dissipation problems especially in nanosized structures. Instead, AC spin currents spin transfer phenomena across – and spin accumulation at – interfaces, play an increasingly important role in many spintronics applications for nanoscale objects.

Key future needs for advanced analytical techniques are (see Fig. 3.3.6):
- The determination of coupling angles and domain structures in magnetic heterostructures and superlattices;
- The precise measurement of magnetisation profile in dilute magnetic semiconductors;
- The real-time measurement of magnetisation reversal and domain formation in exchange-biased systems;
- The microscopic understanding of proximity effects in spin magnets.

A fundamental understanding of the microscopy of the magnetic state of nanomagnets is needed to discover new phenomena. To this end, it is of critical importance to characterise and elucidate the physical and chemical factors that control the magnetic properties of nano-assemblies.

The need for synchrotron radiation and neutron facilities for future research and development of nanomagnetic materials

Synchrotron radiation and neutrons provide a unique and versatile tool to access magnetic systems; they have been vital for the present understanding of magnetism, in particular in complex, small and low-dimensional systems (see Fig. 3.3.7). In nanomagnetism, it is essential that synchrotron radiation and neutrons will offer novel analytical solutions for the study of smaller scale objects, in a shorter timescale and with higher precision.

A major impact of synchrotron radiation and neutrons is expected from:
- Time-resolved experiments on magnetic nanostructures down to picosecond/femtosecond resolution;
- Ultrahigh resolution studies of the electronic structure, giving new insight into electronic band structure and revealing the electronic origin of the anisotropy of magnetic materials;
- Spectroscopic (spectroscopy and nanodiffraction experiments using pump-probe type excitations) and resonant measurements on metal-organic multilayers on the nanoscale;
- Systematic studies of spin structures and spin-quantum fluctuations in artificial superlattices and laterally patterned arrays.

3.3.4. SUPERCONDUCTORS

The discovery of oxide high-temperature superconductors (HTCS) in 1986 gave the field a major new stimulus. However, HTCS present a multitude of materials problems at the atomic or nanometre scale.
**State-of-the-Art**

- Magnetic materials and properties
  - Magnetic semiconductors
  - Magnetic composites
  - Quantum transport
  - Confinement structures
    - Clusters (size, interdistance)
    - Nanopillars & nanowires
  - Nanowires
  - Nanocomposites
  - Molecular nanomagnets
  - Complex heterostructures
  - New spintronics systems
  - Manipulation of spins
  - Organic spintronics

**Synthesis**
- Self-assembled growth
- Nanoscale lithography
- Upgraded cluster techniques
- Computer simulation

**Industrial application**
- Electronics:
  - MIRAM
  - Magnetic recording
  - Devices switching
- Spin – FET, Spin – LED
- Biomedicine:
  - Drug delivery
  - MRI

**Future Needs and Challenges**

- Nanomagnetism
  - Magnetic phenomena:
    - Phase transitions in confinement
    - Dimensional crossover
  - Anisotropy
  - Domain wall propagation
  - Magnetic roughness
  - Exchange bias
  - Magnetisation switching
  - Spin transfer and dissipation

- Nanomagnetic materials
  - Hybrid structures:
    - FM/Insulator
    - FM/Insulator/FM
    - FM/Complementary
  - Nanoparticles & clusters
  - Magnetic semiconductors:
    - Magnetic tunnel junctions
    - Spin-dependent transport

**Advanced Characterisation**
- Enhanced microscopic understanding of:
  - Nanomagnetism
  - Spin dynamics
  - Nanostructure and magnetism
  - Effect of impurities
  - Magnetic characterisation of embedded atoms
  - Local contribution of spin and orbit to momentum

**Industrial application**
- New spintronic devices

**Future Role of Synchrotron Radiation and Neutrons Sources**

- Exploration of new nanomagnetic materials
  - Characterisation:
    - Nanomagnets
    - Nanomagnetic structures
    - Magnetic semiconductors
  - Dynamic effects (down to femtosecond timescale)

**Development of new instrumentation and techniques**
- Complimentary instrumentation integration
- Synchrotron radiation, neutrons and other techniques (MOKE, SPM, SNOM, SEMPMA)
  - Spectroscopy
  - Microscopy
  - Novel instrumentation
- Pump-probe experiments
  - Time-resolved imaging
  - Novel detector systems

---

Fig. 3.17: Roadmap: Opportunities for synchrotron radiation and neutron techniques in the field of nanomagnetic materials.

---

Fig. 3.18: Roadmap on the contribution of synchrotron radiation and neutron techniques to superconductor nanomaterials research.
Fig. 3.3.9 Opportunities for synchrotron radiation and neutron techniques in the field of superconducting nanomaterials.

**State-of-the-art**

New superconductors
- HTS: YBCO, BSCCO, LBCO, Bi2Sr2CaCu2O8, Tl2Ba2CaCu2O8, Bi2Sr2Ca2Cu3O10
- Cuprates (YBCO & BSCCO)
- LBCO
- LSCO
- Interstratified CuO2 layers
- Heavy fermions
- Iron based
- Branched diamond

Advanced synthesis
- Nb, Ti, Nb, Sr, NbAl
- YBCO, Bi2212, Bi2223
- YBCO coated conductors
- Single crystal growth
- High-quality thin films
- Nanocrystalline materials

Superconducting devices
- Multiple-barrier heterostructures
- Planar multi-barrier devices
- Nanoscale heterostructures
- SQUID junctions

Applications
- Power cables
- Accelerators
- MRI, motors, generators
- Condensors, transformers, etc.
- Electronics
- Filters
- Josephson devices (SQUIDS)

**Future needs and challenges**

**Main research activities**
- Materials related issues
  - Search for new superconductors
  - New synthesis & doping techniques
  - Defects and microstructure
  - Nanomaterials
  - Nanomanufacturing
- Fundamental science issues
  - Electronic structure & quasi particle dynamics
  - Magnetism and spin fluctuations
  - Quantum fluctuations
  - Strong correlations
  - Vortices
  - Simple vortex physics
  - Multi-vortex physics
  - Proximity and interface effects
  - Non-equilibrium effects
  - Spin injection
- Nanostructured superconductors
  - New phenomenon & processes
  - Tunnel junctions
  - Nanowire networks
  - Heterostructures & superlattices
  - Nanoclusters
- Advanced synthesis & doping techniques with in-situ control
  - Thin film growth
  - Synthesis at extreme conditions
  - Bulk samples, single crystals, thin films
  - Atomic layer engineering
  - Combinatorial materials science
  - High throughput screening
  - Field-effect & photo-doping
- Advanced characterization of properties
  - Chemical & structural composition
  - Ultrahigh fields
  - Hybrid structures
  - Magic nanoclusters
  - Nanowires
  - "Stripe" order formation
  - Spin fluctuations
  - Electron-phonon interaction

**Future role of synchrotron radiation and neutrons sources**

Fundamental aspects
- Exploration of the HTS coupling mechanism
- Systematic neutron studies of electron-phonon interaction
- Soft x-ray spectroscopy and x-ray diffraction to explore the coexistence of magnetism and SC
- ARPES, XES, RXS, HREELS, XAFS, ITS
- Explanation of quantum fluctuations with neutron and x-ray spectroscopy
- Systematic exploration of thin superconducting films and interface phenomena using grazing incidence diffraction and spectroscopy

Novel materials
- Dedicated x-ray and neutron beam lines for high throughput studies of novel SC materials
- Dedicated x-ray and neutron beam lines for combinatorial materials science

**Breakthroughs**

Breakthroughs in the field of superconductors are intimately related to progress in materials research. The technical performance of HTCS is often superior but production and material costs are still too high. The preparation of bulk superconductors presents particular material problems that are intimately linked to their functionality. In thin-film HTCS, there are many examples of how non-thermodynamic compounds can be stabilised through epitaxy with substrates or buffer layers. Of particular interest in the search for new materials is the phase spread method, where composition gradients in thin films are intentionally introduced. Structural characterisation of such layers during growth requires in-situ technologies with a high level of sensitivity and reliability. These technologies can be provided by the synchrotron radiation and neutron facilities (see Fig. 3.3.8).
Role of synchrotron radiation and neutron facilities

See Fig. 3.3.9. Developments in spectroscopy and electron microscopy (e.g. new detectors) and different scattering techniques (X-ray and neutrons) at the nanoscale will in parallel ensure our ability to study structure and bonding and, ultimately, obtain an atomic level relation between structure and function. As the limits of performance are pushed, the figures of merit of nanostructured superconductors (junctions, wires, clusters, etc.) need to be optimised. Then knowledge about the (sub-)microscopic nature of the structures and how they evolve is crucial. This requires detailed high-resolution characterisation of the microstructure of the devices and a high level of correlation between structure, property and fabrication parameters.

The prime analytical technologies are:
- Angle Resolved Photoemission (ARPES)

For the future, many developments can be expected in ARPES. With higher resolution, it will become possible to explore if one can:
(i) get mean free paths for the low energy excitations comparable to those measured in transport, (ii) resolve the spin charge separated components to the point where we can look at the temperature dependence of each separated component.

- Neutron scattering

Neutron scattering has played a central role in cuprate studies, yielding many spectacular successes including the anti-ferromagnetic parent state and its destruction by hole-doping, the observation of ‘stripes’ and universal spin excitation structure. Neutron scattering studies of the cuprate and other exotic superconductors will play a central role in the future of the field.

- Resonant X-ray Scattering (RXS)

RXS investigations (elastic and inelastic) will become increasingly important for the study of electronic ordering near buried interfaces in materials that have been nanopatterned. Improved scattered energy analysis will also allow for detailed study of ‘fluctuating’ order, and the use of high magnetic fields will allow the study of field induced charge ordering in vortices.

3.3.5. CARBON NANOMATERIALS

The discoveries of fullerences in 1985 and of carbon nanotubes in 1991 opened a completely different perspective from that of carbon materials based on flat graphite-like hexagonal layers. Carbon nanotubes have particularly attracted the attention of many scientists in the wide fields of science and technology as an important component in the realisation of nanotechnology. The synthesis of carbon nanotubes can be accomplished in a wide variety of methods that involve the catalytic decomposition of a carbon sample containing gas or solid. Some of the most common techniques are chemical vapour deposition, arc-discharge, and laser vapourisation synthesis. Nanostructured films with controlled architectures are desirable for many applications in optics, electronics, biology, medicine, and energy/chemical conver-

STATE-OF-THE-ART

Carbon nanomaterials
Model system:
- Basic science
- Nanotechnology
- Building blocks:
  - Integrated devices
  - Nano-electronics
  - Nanoelectromechanics
  - Nanoparticles
  - Nanofluids

Fullerenes
Endohedral systems
Polymerised phases (1-2-3 D)
Structural perfection
Adsortion & storage possibilities

Carbon nanotubes & peapods:
- Ideal model as 1D-solid
- High structural perfection
- Unique structure & chemical stability

Interesting physical properties:
- Metallic
- Semiconducting
- Magnetic
- Superconducting

FUTURE PROSPECTS

Carbon nanotubes
Research activities
- Controlled growth & production:
  - Nanotubes with defined length, diameter and helicity
- Optimise chemical doping
- Upgrade self-assembly
- Separate metallic/semiconductor structures

Fundamental properties:
- Containment-related effects
- Electrical, magnetic, optical, mechanical and thermal
- Correlation between atomic structure and electronic properties
- Inter-tube coupling

Parental applications
Composite materials
Adsortion & storage devices
Electrical & mechanical systems
Battery electrodes
Field emitters
Chemical sensors
Catalysis
Field-effect transistors
Printinng – memories – logic

FUTURE ROLE OF SYNCHROTRON RADIATION AND NEUTRON SOURCES

New synthesis & doping techniques
- In-situ analysis to achieve:
  - Controlled growth and hybrid structures
  - Production of high quality & quantity
  - Synthesis in extreme environments
  - Upgrade purification & separation
  - Optimisation of self-assembly
  - Optimisation of chemical doping of peapods
  - Fabrication of high-strength fibres
  - Nanoelectronic structures

Novel properties
- Advanced characterisation of:
  - Chemical & structural composition
  - Nanotube-polymer composites
  - Transfer processes
  - Interactions metal-nanotube, molecule-nanotube
  - Electron excitation dynamics
  - Architecture of integrated nanotubes devices
  - Nanotube-based opto-electronic devices

Particular challenges
- Single molecule diffraction and spectroscopy:
  - Tailoring of nanobeads
  - Controlling radiation damage (x-rays)
  - Time-resolved diffraction and spectroscopy experiments
  - Inelastic neutron spectroscopy for thermal excitations in ONI arrays

Fig. 3.3.10: Opportunities for synchrotron radiation and neutron characterisation methods for research on carbon nanomaterials.
sions. Low-temperature, aqueous chemical routes have been widely investigated for the synthesis of continuous films, and arrays of oriented nanorods and nanotubes.

The amazing mechanical and electronic properties of the nanotubes stem from their quasi one-dimensional structures and the graphite-like arrangement of the carbon atoms in the shells. Thus, the nanotubes have high Young's modulus and tensile strength, which makes them preferable for composite materials with improved mechanical properties. The nanotubes can be metallic or semiconducting, depending on their structural parameters. However, with our present knowledge of the nanotube growth process, a control of these parameters has not yet been accomplished. This eventually will open the ways for application of the nanotubes as central elements in electronic devices, including field-effect transistors (FET), single-electron transistors and rectifying diodes (see Fig. 3.3.10 and 3.3.11).

3.3.6. DIELECTRIC NANO MATERIALS FOR FUTURE SI-BASED MICRO- AND NANO ELECTRONICS

Advanced dielectric materials are a prerequisite for the improvement of future Si-based micro- and nanoelectronic circuits so as to achieve improved performance, and higher functionality, which has been developed mainly for today's Si-based micro-electronic circuits. Today, the semiconductor industry is paving the way for the transition from micro- to nanoelectronics. This, in turn, will allow for the further improvement of the performance of Si-based IC's. In accordance with the International Technology Roadmap for Semiconductors (ITRS), the development of new dielectric materials will be IC manufacturers' primary goal in making the production of Si-based nanoelectronic devices feasible. In this race for capitalizing on research breakthroughs, synchrotron radiation and modern neutron sources have a large potential to keep the "time to market - periods" of the technology short and European IC manufacturers competitive.

Future research needs and analytical challenges

See Fig. 3.3.12. The research and technology areas of high priority to achieve an in-time transfer of basic research results on dielectric nanomaterials into Si-based micro- and nanoelectronic technologies are:

- To optimise dielectric film preparation and processing techniques
- Film deposition techniques with atomic control for research and industrial needs;
- Adaptability of "state-of-the-art" machinery to integrate dielectric nanomaterials in Si-based nanoelectronic devices.
- To develop characterisation methods for dielectric nanomaterials
- Techniques with high spatial and energy resolution;
- High sensitivity for defect engineering,
- On-line diagnostic capability etc.
- To study materials science of dielectric nanomaterials
- To tailor dielectrics on the nanoscale;
- To evaluate emerging materials concepts for device applications;
- To study the fundamental theoretical understanding of nanodielectrics.

![Fig. 3.3.11: Roadmap for future research on functional carbon nanomaterials.](image-url)
Future role of synchrotron radiation and neutron facilities

Synchrotron radiation and neutron facilities are of key relevance in the successful development of advanced dielectrics for Si-based micro- and nanoelectronic ICs. In order to keep a world-wide competitive position in the nanoelectronics technology, the European Commission must promote the innovation of this important sector of nanomaterials development and encourage a new partnership between university/industry and the synchrotron radiation and neutron facilities. The synchrotron radiation and neutron facilities in turn must provide brilliant beams in the energy ranges of interest; detectors with fast electronics and high dynamic range for nanoscience studies.

The specific needs for the development of advanced dielectrics are:
- High spatial resolution diffraction and spectroscopy beam lines for micro- and nanobeams studies;
- Dedicated beamlines for non-destructive depth profiling of thin films with highest sensitivity to defects;
- Experimental set-ups for high resolution spectroscopy and diffraction studies;
- To reduce "time to market" periods for new nanodielectrics in Si-based micro- and nanoelectronics, the infrastructure of the large scientific test facilities should be adapted and upgraded to the requirements of the IC-industries, this requires:
- Improved beam-time access and use by technology-oriented allocation procedures, user-friendly control and data handling software;
- Synchrotron radiation and neutron beamlines with new level of automation and standardisation.

3.3.7. Conclusions and Recommendations

The properties of synchrotron radiation and neutrons present enormous potential for research and the promotion of innovation in the large field of functional nanomaterials:

- Studying fundamental mechanisms at the atomic level
- Unraveling the complexity in novel materials
- Tuning of functionality
- Tailoring devices
- Processing
- Fabrication

This will imply that the synchrotron radiation and neutron centres will naturally become a focus for the nanomaterials research and technology in Europe. The competitive scientific and industrial interests will push the existing infrastructure capabilities such that it will provide:

Cross-fertilisation
- More intense collaboration between various research communities and industries;
- Technology and knowledge-transfer through multi-disciplinary research & development.

Infrastructure
- Real time, in-situ experiments – down to sub-picoseconds;
- Nanoscale focus of experiments – spatial resolution better down to 10 nanometres;
- Atom-selective spectroscopy – ability to resolve microscopic environments;
- Surface and interface sensitive diffraction and spectroscopy experiments – Essential for the study of all important interfaces of composites;
- New imaging, tomography and microscopy techniques;
- Soft (destruction-free) probes for organic and biological nanomaterials.

Public Awareness
- Make facilities attractive to young scientists, non-specialists, commercial/industrial clients;
- Provide more training programmes. University "road shows".

Scientific Breakthroughs
- Clarify how electronic, optic, magnetic properties depend on atomic structure (superconductors, carbon nanotubes, magnetic materials, 3D atomic structure usually cannot be determined by other techniques);
- Identify the bottlenecks in material and device design by defect characterisation, in-situ and in-vivo characterisation, measurement of otherwise inaccessible material properties in the material volume;
- Develop "local diffraction probes" by nanobeams, to combine and correlate spatially resolved diffraction and imaging results with other locally resolving methods like microscopy, micro-photoluminescence (this will in the near future only be possible at synchrotron radiation sources);
- Investigation of buried interfaces in composite materials, which are most of the functional materials discussed. This can only be achieved with synchrotron radiation and neutron scattering. Nanotechnology aims also to imitate natural materials, which are to large extent composite materials, where the interface properties dominate or entirely determine the material properties.

The impact of synchrotron radiation and neutron on the development of new functional nanomaterials is given in the following diagramme (see Fig. 3.3.13).

Overall Guidelines

Several specific measures and recommendations for the future use of synchrotron radiation and neutrons can be formulated, corresponding to different timing periods to both policy makers and facilities.

In the short term:
- Upgrade existing sample environment: low temperatures, high magnetic fields and pressures, availability of in-situ growth chambers;
- Install secondary lab-based characterisation techniques for simultaneous measurements;
- Improve detector technology: 2D-detectors, He "hemispherical" detectors, faster read-out, better dynamic range etc.
### Dielectric Nanomaterials for Future Si-Based Micro- and Nanoelectronics

#### Future Applications

<table>
<thead>
<tr>
<th>Logic Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon-on-Insulator (SOI)</td>
</tr>
<tr>
<td>Low-k Interlayer Dielectrics</td>
</tr>
<tr>
<td>High-k Gate dielectrics</td>
</tr>
<tr>
<td>Ferroelectric Gate dielectrics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-k materials</td>
</tr>
<tr>
<td>Dynamic Random Access Memories (DRAM) and Flashcells</td>
</tr>
<tr>
<td>Ferroelectric materials</td>
</tr>
<tr>
<td>Ferroelectric Random Access Memories (FRAM)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Various dielectrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel oxides for Magnetic Random Access Memories (MRAM)</td>
</tr>
<tr>
<td>Phase Change Random Access memories (PCRAM)</td>
</tr>
<tr>
<td>Holographic data storage, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless communication</td>
</tr>
<tr>
<td>1) Dielectrics for Meta-Insulator-Meta (MIM) capacitors</td>
</tr>
<tr>
<td>2) Surface Acoustic Wave (SAW) Filters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave Communication Systems</td>
</tr>
<tr>
<td>Neuroelectronic Interfacing</td>
</tr>
<tr>
<td>Diagnostic Devices</td>
</tr>
<tr>
<td>Lab-on-Chip solutions</td>
</tr>
<tr>
<td>Sensors</td>
</tr>
<tr>
<td>Electronic Noses</td>
</tr>
<tr>
<td>Pyroelectric IR Detectors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Research and Development Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
</tr>
<tr>
<td>Atomic scale control (mass flow, oxygen pressure etc.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Techniques</td>
</tr>
<tr>
<td>Leakage, dielectric constant and loss, detects and interface states</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials Science Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>High sensitivity</td>
</tr>
<tr>
<td>Non-invasive character</td>
</tr>
<tr>
<td>High spatial resolution</td>
</tr>
<tr>
<td>High energy resolution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-down and bottom-up approaches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
</tr>
<tr>
<td>Materials manipulation in the nanoscale (global and local approaches etc.)</td>
</tr>
<tr>
<td>Materials for new device concepts and physics (oxide electronics, spintronics, orbitronics etc.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth kinetics, thermodynamics, electric properties etc.</td>
</tr>
</tbody>
</table>

### Challenges for Synchrotron Radiation and Neutron Facilities

#### Sensitivity

**Machine**
- Adequate brilliance in the different energy ranges

**Detectors**
- Fast electronics of high dynamic range

#### Resolution

**Spatial resolution**
- Beamline optics for micro- and nanobeam studies
- Experimental techniques for non-destructive depth profiling

**Energy resolution**
- Experimental set-ups for high-resolution spectroscopy and diffraction studies

#### Various

**Beamline access**
- Technological-oriented evaluation procedure
- Quick access upon demand for successful proposals

**User Friendliness**
- ISO-certified beamlines
- Control and data handling software

---

Fig. 3.12: Dielectric nanomaterials for future Si-based micro- and nanoelectronics – challenges for synchrotron radiation and neutron facilities.
- Develop hybrid scattering experimental techniques;
- Explore the potential of combined neutron and synchrotron beam lines (not absolutely necessary – the samples can also be transferred but this should be facilitated);
- Stimulate the interaction between modelling methods to the experimental measurements, with a longer term view of using the predictive capabilities to direct experiments in nanomaterials sciences;
- Increase attractiveness for non-specialist users (for instance by providing user-friendly sample environment and automatic data analysis procedures) and to create a fast access lane for exceptional exploratory test experiments;
- Users would welcome faster turn-around times between submission of project proposals and actual experiments at the synchrotron radiation and neutron facilities. The long delay between submission of proposals, uncertainty of approval and eventual allocation of beam time makes the incorporation of synchrotron radiation and neutron experiments into any research project unattractive. Nevertheless, there are provisions for industrial projects at any synchrotron source to get speedy access and turnaround. Basic research projects just need to be of sufficiently high scientific quality.

As a long-term project, there should be a considerable investment in the infrastructure: new dedicated beam lines and detector development, creation of 'Centres of Excellence' in specific nanoresearch fields, user-support facilities.

Most of the leading industrial research is already carried out outside of Europe and it may be expected that the European neutron drought will undoubtedly lead to a similar situation for academic research. Europe has to present all the effort needed to allow it to maintain its position as a global leader in the development of novel LINAC-based x-ray and neutron sources.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Semiconductor heterostructures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem</td>
<td>How do properties depend on interface structure</td>
</tr>
<tr>
<td>Solution</td>
<td>Scattering experiments using SRM scattering</td>
</tr>
<tr>
<td>Functional Nanomaterials</td>
<td>Access buried interfaces destruction-free, in-situ if required</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topic</th>
<th>Photonic materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem</td>
<td>What are the bottlenecks limiting material and device properties and design</td>
</tr>
<tr>
<td>Solution</td>
<td>In-situ and in-vivo studies during material fabrication and device operation</td>
</tr>
</tbody>
</table>

Fig. 3.3.13. Schematic overview for the needs of synchrotron radiation and neutrons.