

# 2011 – A Nanospace Odyssey

*The European White Book on Fundamental Research in Materials Science\* has been compiled by the **MAX PLANCK INSTITUTE FOR METALS RESEARCH**, and published by the Max Planck Society. It is a compendium of current conditions and developments in the metal sciences in Europe, although it is also an urgent plea for change, that is, for scientific support programmes to place greater emphasis on fundamental materials research without which we shall not be equipped for the technological challenges of the more distant future. **PROF. HELMUT DOSCH**, a director of the Max Planck Institute for Metals Research, co-author and co-editor of the White Book, discusses the prospects and obstacles of the project.*

In this day and age, little that happens in modern industrialised countries does so without the use of sophisticated high-tech materials. Made-to-measure materials and materials systems are the basic building blocks of all modern technology, starting with information and communications, medicine, energy and the environment, right up to transport. As a rule we are barely conscious of the fact that we regularly use important products from the laboratories of solid-state researchers and materials scientists.

In the last few decades, the development of new materials, including the nano-structures and high-tech products that are based on them, has progressed at a simply breathtaking rate. Just think of semiconductor technology, which, every six months or so, provides us with computers that are faster, smaller, and have larger

memories than before. Even musical greeting cards contain more computational power than was available to the Allies during the Normandy landings. Nowadays we take high-resolution, high-performance LED flat screens for granted. As the aging process catches up with us, we can take advantage of a wet weekend to have our crumbling hips replaced with high-tech titanium joints. News broadcasts about astronauts who fit new lenses on myopic satellite telescopes whilst travelling at 280,000 kilometres per hour are considered by most of us as just another routine item. Using your mobile to give the ex a quick call from the ski slopes where you're having a marvellous time (only to discover that she's sunbathing

\* European White Book on Fundamental Research in Materials Science, Manfred Rühle, Helmut Dosch, Eric J. Mittemeijer, Marcel H. van de Voorde, Max Planck Institute for Metals Science, Stuttgart (ISBN 3-00-008806-7)

COLLAGE: DOSCH / MAX PLANCK INSTITUTE FOR METALS SCIENCE

in Mexico) is already considered hopelessly old-fashioned. Only fifty years ago, all of these things would have been regarded as the stuff of science fiction, and would have filled some people, especially amongst us sceptical Germans, with sheer horror.

Not one of these modern high-tech adventures would be in the slightest bit conceivable if it were not for the existence of material structures and architectures with made-to-measure electric, magnetic or optical properties – frequently weighing very little –, which can withstand the highest mechanical and thermal loads. How did this undeniable triumph of materials science, which has so altered our lives and so enormously raised our standard of living, come about? How did it all begin?

Basically, the success of modern materials science has been made possible because we have essentially understood the structure and properties of condensed matter at the scale of nanometres, and are able to control them. The epoch of materials science, which is oriented towards the microscopic, began almost precisely one hundred years ago: this is when the laws of quantum mechanics (which describe the physical - and chemical - phenomena of the nano-cosmos) and X-ray diffraction (which allowed us to look at the atomic structure of condensed matter) were discovered. The driving force for these pioneering achievements were scientific curiosity and the natural human instinct to strive for an understanding of the world we live in.

### Hurdles on the Horizon

These new theoretical and experimental tools enabled scientists to arrive at fundamental new insights into solid-state physics, reveal their detailed structures and the movement of electrons in these complex, atomic multi-particle structures. Some of the major by-products of this fundamental research include semiconductors and transistors and, more recently, ceramic high-temperature superconductors and iron-chrome nano-structures. The latter exhibit electrical resistance, which is highly dependent on magnetic fields, and are used today as read heads in all modern hard disk storage systems.

The knowledge that has been accumulated over the last century on how solids function on an atomic level now permits us to produce materials systems in a targeted and reproducible way with properties that are made-to-measure to fulfil our requirements. This is the domain of so-called applications-oriented materials scientists whose task it is to think and work in terms of problem solving rather than curiosity-driven, and to provide elegant scientific solutions to complex actual materials problems within predictable (and preferably short) time spans. This kind of applications-oriented materials science broadens our understanding and our

technology in an, as it were, evolutionary fashion – by the kind of incremental and predictable developments that are particularly typical of industrial research. A prime example of this is the well-known Moore's Law, according to which the density of transistors in integrated switching circuits doubles once every 18 months. However, applications-oriented materials research also has to rise to the challenge of expanding the commercial potential of materials by, for instance, reducing manufacturing costs, extending their useful lives, or improving their environmental friendliness (recycling).

The achievements made by means of this evolutionary materials science are irrefutable. Scientific policy makers (and hence funders) have therefore found it very tempting to concentrate on promoting applications-oriented research since this transforms research funding into products more or less at the touch of a button. Nevertheless, it is obvious to the experts that a research funding system aimed exclusively at solving tomorrow's technological problems poses a huge danger to the future development of a knowledge- and technology-based society for the day after tomorrow. The signs are already ominous. Within the next ten to twenty years, much of today's technology will hit stumbling blocks of fundamental physics (so-called 'show stoppers') that will not be surmountable by evolutionary means. As an example I need only refer to the above-mentioned integrated circuit technology, which, in accordance with Moore's Law, will encounter transistors of atomic dimensions in approximately twenty years time. However, the basic problems begin much earlier than that, namely at a few tens of nanometres.

If only to overcome those future hurdles which can already be seen on the horizon, we must today put some hard work into basic research – in the hope that we will be able to discover and comprehend new revolutionary concepts, phenomena and materials with which to realise future technology in good time. The store of ideas held by fundamental researchers is not at all bad, it ranges from single electron transistors, quantum and light computers, magnetic electronics that draw on the electron spin, data storage media the size of pinheads, chips with the dimensions of dust particles ('smart dust'), right down to new, super-hard materials that make steel seem as soft as butter. This gives us a flavour of how science fiction could become reality in fifty years time if we approach the 'fundamental science-oriented materials research' adventure with verve, and do so right now.

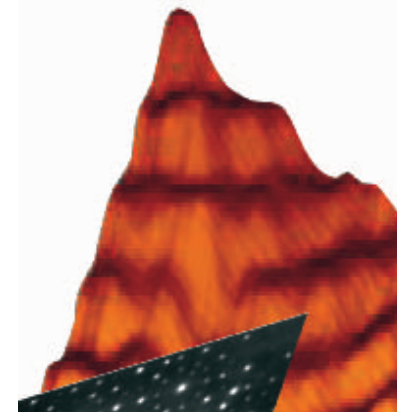
Unfortunately, unpredictability is in the nature of all fundamental research. No fundamental research scientist can seriously tell his or her financial backers that – and certainly not when – he or she will be successful. Revolutions just cannot be planned for; the most any-

one can do is spur them on. Ever since the year dot this is precisely what has pushed unworldly scientists driven by curiosity into a permanently defensive social position.

A meeting between Michael Faraday, who was already famous by then, and King William IV provides a true, or at least well invented and definitely symptomatic story: asked what good electricity would do, the wily Faraday responded that it would one day provide the King with a huge amount of tax revenue. Modern versions of this 'justification' can be found in many a physics publication today. If an author blathers on about 'potential applications' in the introduction to his article, we may assume he is trying to ensure that government funding of his fundamental research project is not suddenly cut off.

The European White Book on Fundamental Research in Materials Science, published in November 2001, is the first broad-based attempt to draw attention to the yawning funding gap in fundamental research that has so far prevailed in the context of European support programmes, and to achieve the implementation in Brussels of a long-term European funding strategy for fundamental research. Every noteworthy European institute and centre of materials science has contributed to compiling a report on the status and prospects of fundamental research-oriented materials research, and has been involved in drawing up the European funding policy measures that are urgently required if the technological continent of Europe is to remain - or become - competitive against the USA, Japan, and the tiger economies that are currently developing at a very fast rate. Naturally, one of the things the White Book clearly emphasises is that what matters in the first instance is sufficient and long lasting funding. Particularly as regards basic research projects, enduring funding is a 'conditio sine qua non' since these projects are long-term, i.e., they are generally planned to run for longer than the half life period of support programmes.

In addition to this purely financial aspect (without which, naturally, nothing can work), the authors of the White Book point to a number of structural and cultural problems that currently confront fundamental research, and which have to be solved on a national and European level. One of these problems concerns the social acceptance of basic research: especially among the young (i.e. the potential next generation of scientists), the popularity of the natural sciences has suffered severe blows in the last few decades. The average young person nowadays associates physics with Chernobyl, nuclear waste, and nuclear weapons, chemistry with Seveso and poisoned rivers, and biology with BSE, ge-



netically modified tomatoes, and cloned sheep. The latest media attacks on allegedly idle professors employed by inefficient universities who twiddle their thumbs at the taxpayers' expense, have further aggravated the situation. The most intelligent school leavers no longer

study physics and chemistry (as used to be the case), but prefer to go into business.

Some responsibility for this disastrous development also lies with the ivory tower mentality of fundamental researchers themselves. For many years they neglected to make any attempt to make their research work transparent to the broader public. So far, the only commendable exceptions have been high-energy and astro-physicists who have always known how to make the 'adventure of science' accessible to wider society with appropriate language. In the meantime, nearly all institutes and centres of materials science have begun the long overdue process of mending their ways:

Open days, popular science events in the evening and taster courses for school children are right at the top of the agenda where deans and institute directors are concerned. Early results appear to be vindicating their efforts. The downward trend of student-intakes has generally been halted, and student numbers for physics and chemistry courses are on the rise again (although not just thanks to public relations work).

### Science needs Society

It is my opinion that national measures will have to be taken first. For instance, teachers of physics and chemistry should be offered long overdue further training opportunities to ensure that the teaching of physics and chemistry can keep up with current developments (which can be tremendously fast at times). It should be a matter of course for physics and chemistry lessons to include discussions in comprehensible terms of the contemporary scientific achievements that have been rewarded with Nobel Prizes for physics or chemistry.

We Germans seem to have a particular penchant for formal education. Our school leavers and graduates are lacking what the Anglo-Saxons term 'literacy', i.e. the ability to refer to and apply acquired knowledge in a targeted way. This is precisely what will distinguish the high-tech problem-solvers of the future. The term interdisciplinary education often comes up in this context. This is particularly popular in materials science, which depends on the synergetic collaboration of physicists, chemists, biologists and engineers. The structure of today's school and university education is defined by a distinction between disciplines. And this



is a good thing, as there is no sensible alternative to a solid basic education in physics, chemistry or biology.

Taking an over-actionistic approach to meeting the requirement for interdisciplinarily educated school children, i.e. replacing the school subjects physics, chemistry, and biology with one simply entitled 'science' (as is already happening), will be a disservice to the whole idea. This will produce school leavers who know a bit of everything, but do not have a deep understanding of anything. In my view, interdisciplinarity is a very difficult component that must be considered very carefully before it is integrated in the education system. Otherwise, we shall achieve the exact opposite of what we were aiming for.

In this respect there is a great deal that could be done at a European level, firstly to make young people receptive to the adventure of the natural sciences, and also to integrate interdisciplinary elements into their education. How about doing something completely different, such as holding three-week 'Summer Training Camps on Natural Sciences' on Malta, Crete, or Corfu for the each year's most successful school students? There would be science in the mornings and after dinner, sunshine and fun in the afternoons, and a graded

materials scientists of tomorrow will build made-to-measure materials, atomic layer by atomic layer, or even atom by atom, thereby creating atomic configurations with completely new properties that do not occur in these forms in nature.

Revolutionary discoveries are expected for the future, especially as a result of so-called hybrid nano-structures where super-conducting components meet with magnetic components, magnetic with semi-conducting, semi-conducting with organic, and organic components meet with metal components on a nanometer scale.

As serious scientists we cannot - and should not attempt to - issue reliable forecasts about the new phenomena and materials structures that are waiting to be discovered within the next fifty or even hundred years, nor should we hazard a guess at which of these could be exploited for new technologies. However, we can presume that there will be a revolution in solid-state physics, materials science, chemistry and biology, which even hard-bitten physicists, chemists and biologists have been known to go into raptures about: a capacity for technical analysis whereby the movement of atoms in condensed matter during chemical reactions or biological processes can be observed in real time, that is, within a few thousand million millionths of a second. This would enable us to watch nature as it is working, as it were, thereby allowing us to solve a few of nature's troublesome riddles. How is a liquid, which is randomly organised, transformed into a perfectly ordered crystal when cooled? How is a chemical bonding created? How do pharmaceutical drugs work?

Conducting holographic observations on the scale of nano-metres would also require a fully coherent X-ray, that is, an X-ray laser. Until a few years ago, the idea of an X-ray laser with a pulse of femto-seconds was no more than a pious hope, even for the more optimistic physicists. It now seems that this could actually be realised within the next five to ten years if everything runs as DESY in Hamburg would like it to. DESY have recently presented technical proposals for just such a huge, futuristic project (TESLA-XFEL), and have already managed to get such a 'free electron laser' into operation.

It is possible that some of these bold dreams will not be realised as rapidly as we hope.

However, the intelligent examination of these 'big bang questions' that arise from the nano-cosmos of condensed matter will attract an intellectual elite on whom any future European society based on knowledge and technology will be dependent to as great an extent as it will on the development of new technologies. ●

### A Big Future for Small Structures

certificate to take home for everyone who passes the final exam. The whole thing should have a strongly European component, here too the lingua franca would be English, and the participants should come from as many European member countries as possible. If this were also to promote the mobility within Europe of our youngsters, then such an institution would be more than worthwhile.

Finally, let us just assume for the sake of argument that we do acquire a hold on social attitudes and the problem of education (PISA aside, rays of hope are beginning to appear on the horizon). What are the specific future challenges as regards materials? Here, too, the White Book provides us with detailed information: European experts have identified several key fields of research that should be tackled by means of concerted European action. The recommendations with highest priority include research into new phenomena and materials as well as interdisciplinary research strategies. According to the experts, intelligent ('smart') materials, bio- and nano-technologies will be among the next ten years' fastest growing areas of materials science. We can expect achievements in nano-technology that will bring further dramatic changes to our everyday lives. The ma-