Appendix C. European Roundtable Discussions

STUTTGART ROUNDTABLE

Site: Stuttgart, Germany

Date: 13 October 1997

WTEC: C. Koch (report author), D. Cox, E. Hu, R.W. Siegel

Attendees:

<u>University of Ulm</u>
Prof. Dr. Peter Unger, Associate Professor, Dept. of Optoelectronics
Prof. Dr. Hans-Jorg Fecht, Fakultät für Ingenierwissenschaften, Abt. Werkstoffe de Elektrotechnik
Prof. Dr. Rolf Jurgen Behm, Abteilung Oberflachenchemie und Katalyse, Fakultat für Naturwissenschaften
Prof. Dr. R.-P Franke, Zentralinstitut für Biomedizinische Technik, Abteilung Biomaterialien
Prof. Dr. Witold Lojkowski, Abteilung Werkstoffe der Elektroechnik
Dr. Joachim Spatz, Abteilung Oberflachenchemie III, Fakultat für Naturwissenschaften

<u>Max Planck Institutes</u>
Prof. Dr. Klaus v. Klitzing, Max-Planck-Institut für Festkörperforschung
Dr. I.M.L. Billas, MPI für Festkörperforschung
Dr. P. Redlich, MPI für Metallforschung
Dr. Thomas Wagner, MPI für Metallforschung

<u>Others</u>
Prof. Dr. Manfred Kappes, University of Karlsruhe, Inst. Physikalische Chemie
Dr. Victor Trapp, Project Manger, Fuel Cells, SGL Carbon Group, SGL Technik GmbH
Dr. Margret Wohlfahrt-Mehrens, Electrochemical Material R&D, Solar Energy and Hydrogen Research Center
Dr.-Ing. Wolfgang Kleinekathofer, Daimler Benz AG, Forschung und Technik

A group of scientists from or near Stuttgart were invited to a roundtable discussion of their various research projects on nanoscale technology and materials. Names of attendees and their affiliations are listed above. The highlights of these presentations are given below, by institution.

Max-Planck-Institut für Festkörperforschung (MPI FKF)

Tel: (49) 711-689 0; Fax: (49) 711-689 1010
http://www.mpi-stuttgart.mpg.de/start.html

Professor Dr. Klaus v. Klitzing

Professor v. Klitzing described research on functional nanodevices at the Max Planck Institute (MPI). He also discussed the broader view of work on nanotechnology in Germany, particularly on III-V quantum structure devices. Summaries of work on this subject, financial supporters, and details of technical progress are summarized in *III-V-Elektronik Mesoskopische Bauelemente* (in German). There is broad cooperation between universities and industry on this project. Professor v. Klitzing briefly described some of his own research, including MBE growth and etching system for study of GaAs/AlAs/ AlGaAs:15/AlAs:6/GaAs and quantum dot lasers GaInP and InP. The ultimate single-electron tunneling transistor—which is being addressed at many laboratories—is the goal of much of the research.

The electronic properties of clusters are studied, e.g., gold clusters with well-defined number of atoms as contacts and islands for charge transfer. Some examples of low-dimensional electronic systems prepared by the chemistry department of the MPI FKF Stuttgart are "0-dimensional" $CS_{11}O_3$, "one-dimensional" Na_5Ba_3N, and "two-dimensional" Ba_2N crystals. Prof. v. Klitzing is skeptical about the ultimate use of nano-semiconductor systems, such as quantum dots, for applications in mainstream microelectronics.

Dr. I.M.L. Billas

Dr. Billas in the group of Prof. Dr. T.P. Martin described the group's work on clusters studied by means of time-of-flight mass spectrometry. Much of the work deals with metal-covered C_{60} or C_{70} molecules. C_{60} is an ideal template for growing shells of metal atoms. Several systems include alkali-metal, alkaline-earth-metal, and transition-metal-covered fullerenes. Fabrication of new exotic magnetic nanostructures is part of an interregional research project "magnetic nanostructures," which includes researchers from adjacent regions of France and Germany partially funded by regional governments. The project collaborators are listed below:

France: *Rhône-Alpes region*:
Dr. A. Perez, University C. Bernard, Lyon
Prof. Dr. M. Broyer, University C. Bernard, Lyon
http://www.univ-lyon.fr/
Prof. Dr. B. Barbara, CNRS, Grenoble
Dr. K. Hasselbach, CNRS, Grenoble
http://labs.polycnrs-gre.fr/
Alsace region:
Prof. Dr. J.-P. Bucher, University L. Pasteur, Strasbourg
http://www-ulp.u-strasbg.fr/

Germany: *Baden-Würtemberg region*:
Prof. Dr. H. Haberland, Frieburg University
Prof. Dr. T.P. Martin, MPI, Stuttgart
Prof. Dr. D. Weiss, Stuttgart and Regensburg

The research of this program includes fabrication and stabilization of nanosize magnetic structures (magnetic dots and clusters) and their characterization by time-of-flight mass spectroscopy, TEM and HRTEM, XRD, and absorption techniques, Rutherford Backscattering, and XPS. Magnetic properties are measured by magnetic force microscopy, magnetometry (microSQUIDs), magnetotransport measurements, and ultrafast magnetooptical measurements.

Max-Planck-Institut für Metallforschung

http://wwwmf.mpi-stuttgart.mpg.de/

Dr. Thomas Wagner

Dr. Wagner is staff scientist at the Max-Planck Institut für Metallforschung leading the "Thin Film Synthesis and Processing" group. His current research uses STM, TEM, coupled with standard surface analysis techniques, to characterize metal and ceramic films, multilayers, and alloy films with defined chemical composition grown by MBE and sputter deposition on a variety of substrates. The main thrust of his group is to investigate physico-chemical mechanisms of thin film growth like solid state reactions, nucleation processes, and interface formation during film deposition. The following thin film systems are under investigation:

Metal/Ceramic	Nb, Cu/Al_2O_3	Al, Ag/$MgAl_2O_4$	Si, Pd, Cu/$SrTiO_3$
Ceramic/Ceramic	Ti_2O_3/Al_2O_3	ZrO_2/Al_2O_3	TiO_2/Al_2O_3

In addition, special thin film systems are grown to study their mechanical properties (e.g., alloy films), thermal stability (grain growth, stability of boundaries), atomistic structure, and bonding interfaces.

Prof. Dr. Manfred Rühle

The main thrust of Prof. Rühle's group is use of state-of-the-art analytical tools to study materials and thin film microstructures and interfaces. One major goal of the research is to correlate chemical composition and microstructure of materials to their macroscopic properties. In this context, it is of fundamental interest to quantitatively investigate and model the growth, atomistic structure, and bonding at interfaces of both real materials and model systems. Such model systems are fabricated by different techniques, like ultrahigh vacuum diffusion bonding and molecular beam epitaxy. Major research activities are concentrated on electron microscopy and interfacial research. Analysis is carried out with tools such as HRTEM, analytical electron microscopy (AEM), and surface science techniques. Interfaces of these material systems have been studied both experimentally and theoretically: grain boundaries in metals, intermetallics and complex oxides, and metal/ceramic phase boundaries, including the following:

metal/metal:	NiAl/NiAl	Cu/Cu	
metal/ceramic	Nb, Cu/Al_2O_3	Al, Ag/$MgAl_2O_4$	Pd, Cu/$SrTiO_3$
ceramic/ceramic	Al_2O_3/Al_2O_3	$SrTiO_3$/$SrTiO_3$	

Major research interests include those listed below:

1. processing of clean and well-defined surfaces and interfaces by diffusion bonding and MBE
2. growth and surface studies by modern techniques of surface science
3. quantitative investigation of materials, interfaces, and solid state reactions by high resolution (transmission) electron microscopy (HREM), analytical electron microscopy (AEM), and energy filtered convergent beam electron diffraction (CBED)
4. refined quantifications of results from electron microscopy investigations by methodical developments
5. computer simulation of boundary structures and bonding at interfaces by different techniques (e.g., *ab initio* methods)

Dr. P. Redlich

Dr. Redlich is also in Prof. Rühle's institute. His research interests are in the field of carbon nanofibers. Institute researchers use arc-discharge methods to synthesize their carbon nanotubes. They are also studying chemically modified C nanotubes. Using BC_4N as an anode they obtain a new material. They use HRTEM and EELS to characterize their materials. The interdisciplinary approach to these studies is emphasized with collaborations with experts in synthesis and characterization within MPI, Germany, and the United States.

University of Ulm

Albert-Einstein-Allee 45, D-89081 Ulm, Germany
http://www.uni-ulm.de

Prof. Dr. Peter Unger
http://www-opto.e-technik.uni-ulm.de/index-e.html

Dr. Unger is in the Department of Optoelectronics of the University of Ulm (K.J. Ebeling, Director). Research topics in the university include vertical cavity surface emitting lasers (VCSELs), Gbit data transmission using VCSELs, high-power semiconductor lasers, and nitride-based semiconductors (for LEDs, lasers). The funding of this research comes from the German Ministry of Education, Science, Research, and Technology (BMBF), Baden-Württemberg, German Research Society (DFG), the European Union, and industry (Siemens, Daimler-Benz, Telekom). The equipment used includes MBE (for GaAs, AlGaAs, InGaAs), GSMBE (for InP, GaInAsP, AlGaInP) and MOVPE (and GSMBE) for GaN, InGaN, and AlGaN. Lithography is both optical and e-beam, and dry etching is by RIE, CAIBE. Nanotechnology studies include epitaxial growth (quantum wells, nanometer accuracy, nanometer reproducibility) and lithography and dry etching (holograms, waveguides, and laser mirrors). No structures have nanometer-scale dimensions, but they do have nanometer-scale definition, accuracy, and side wall roughness.

Prof. Dr. Hans-Jorg Fecht

Dr. Fecht is in the Faculty of Engineering, Department of Electronic Materials/Materials Science. Dr. Fecht has a number of basic research and applied research projects, many of which involve nanoscale science and technology. The per-year funding level is about $1.2 million. Eight projects are of particular interest for nanostructured materials research:

1. structure and properties of nanocrystalline (nc) materials prepared by cyclic mechanical deformation
2. high temperature mechanical properties of ceramic thermal barrier coatings
3. tomographic nanoanalytical microprobe/field ion microscopy
4. small angle neutron scattering of nanostructured materials
5. optimization of the wheel/rail contact for high speed trains—development of new steels that are more prone to the formation of nc surface layers due to friction-induced wear, as well as testing of nc coating technologies

6. development and modeling of nanostructured wear resistant coatings—examples are Ti-Al-N, SiC, and Fe-Cr-Si/WC to improve lifetime of wear parts and biomaterials (e.g., stents, pacemakers, etc.)
7. “Simulation of Microsystems,” a materials databank for materials used in microsystem technologies, including thin films and coatings and bonding technologies: development of physical models to describe the thermomechanical properties of nanostructured materials in microsystems
8. sensor clusters in extreme environments: development of new sensors that can withstand extreme current densities, temperatures (up to 1300 K) and pressures (2000 bar) using surface acoustic wave devices; new metallization schemes using nc/amorphous phase mixtures; and nc diamond as a new material for pressure sensors

Prof. Dr. Rolf Jurgen Behm

Dr. Behm is in the Faculty of Sciences, Department of Organic Chemistry and Catalysis. He described the fabrication of nanostructures by scanning probes. These included semiconductor materials where, e.g., scanning tunneling microscopy was used for direct local deposition of Si or $Si\text{-}H_x$ species from a SiH_4 precursor gas on the Si(111)–(7x7) surface. Direct writing of nanostructures with lateral dimensions down to 40 nm is accomplished; similarly, nanofabrication of small Cu clusters on Au (111) electrodes is accomplished with the STM. Work is also carried out on the chemical properties of defined multicomponent particles of interest for catalysis. It is suggested that bimetallic catalysts may have a future, compared to single-component monolayers, which are too expensive. About 80% of this research is directed toward fuel cell catalysis. These programs are funded by government (BMBF, DFG, EU) and industry.

Dr. Margret Wohlfahrt-Mehrens
Center for Solar Energy and Hydrogen Research, Baden-Württemberg, Department of Electrochemical Material Research and Development

The major function of the Center for Solar Energy and Hydrogen Research is to characterize materials—some of which may be nanostructured—for batteries, supercapacitors, fuel cells (direct methanol), and hydrogen storage (fuel cell, carbon nc materials). The center obtains its materials from others, since it does not make materials. At this time it is not possible to predict whether nanostructured materials will be useful in the above applications.

Prof. Dr. R.-P. Franke

Dr. Franke is in the Central Institute for Biomedical Technology, Department of Biomaterials. Dr. Franke described several interesting studies related to the interfaces between biomaterials and tissues. One study (funded by BMBF) involves the tribology of implants under load. The wear particles of the implant can be in the size range of nm to mm and lead to inflammation of the tissue and subsequent loosening of the implant. Nanostructures may be important in filtering devices, sensors, and artificial organs. Specificity—specific reactions by receptors—is important in organisms, while biomaterials typically react by nonspecific reactions. Placement of receptor-like molecules on biomaterials by nanomanipulation methods should open new opportunities. In general, there appear to be many new exciting research possibilities in the fields of wear, mechanical, and chemical properties of nc biomaterials.

Prof. Dr. Witold Lojkowski

Dr. Lojkowski is in the Department of Electronic Materials/Materials Science as visiting scientist from the Polish Academy of Sciences, High Pressure Research Center in Warsaw, Poland (a Center of Excellence). His major research interests at Ulm involve characterization of nc powder and high pressure sintering. In terms of characterization of nanomaterials, X-ray diffraction analysis is the methodology used. Ab initio calculations are made of diffraction spectra for model structures and compared with the experimental data. Information about size, shape, strain, and polytype-structure of the nanopowders is obtained.

Studies of the sintering of nc SiC and nc diamond are carried out at pressures up to 40 GPa and temperatures up to 2000°C. In situ X-ray diffraction studies are made under pressure to determine the processes taking place during sintering.

Dr. Joachim Spatz

Dr. Spatz is in the Faculty of Sciences, Department of Organic Chemistry/Macromolecular Chemistry (director, Dr. Marten Möller). He described his department's research on using diblock copolymers in ultrathin films for patterning. The phase organization of the diblock copolymers into micelles can be arranged in various ways on substrates. The distance between clusters can be about 10 nm and modified by changing the molecular weights. The chemical inhomogeneity of the diblock copolymer films can be used to deposit metals locally on either block "A" or "B." This can provide masks on the nanometer scale with the limit so far of about 30 nm. Another method to approach limits of 1 nm uses the addition of metal compounds in solution to the core of a copolymer, then reduces the metal compound to the metal. An example is Au nanoparticles about 6 nm in diameter with the distance between them controlled by the polymer. Oxygen plasmas can be used to remove the polymer with the metal particles remaining in place. The particle size can be reduced with lower molecular weight polymers. Precise islands 5–20 nm and 10-200 nm apart can make high density quantum dot arrays, 1,000 dots/mm^2.

University of Karlsruhe

http://www.uni-karlsruhe.de

Prof. Dr. Manfred Kappes, Institute of Physical Chemistry

Prof. Dr. Kappes briefly described the scope of their work related to nanostructures. This includes studies of fullerenes, electronic structure of clusters, and use of clusters as projectiles to make well-defined defects on substrate surfaces. The details of the work in Prof. Dr. Kappes' laboratory are given in the report of the site visit to Karlsruhe (Appendix B).

SGL Technik GmbH

http://www.sglcarbon.com/welcome.html

Dr. Victor Trapp, Project Manager, Fuel Cells, SGL Carbon Group

Dr. Trapp provided an industrial perspective on work on carbon nanofibers as part of a large, $1 billion per year, carbon company business. The present cost is about $30/lb. The carbon nanofibers may be used in composites (for automotive, electronics applications), electrochemistry for electrodes, etc., and hydrogen storage. An industrial concern with carbon nanofibers is potential or possible health/environmental problems. This is a major obstacle to commercialization.

SWEDEN ROUNDTABLES

Site: **Royal Institute of Technology (KTH)**
SE-100 44 Stockholm, Sweden

Date: 15 October 1997

WTEC: D. Cox (report author), C. Koch, J. Mendel, R.W. Siegel

Hosts: Prof. K.V. Rao, Department of Condensed Matter Physics
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Attendees:

Docent Ingela Agrell, Foundation for Strategic Research
Prof. Tord Claesson, Dept of Physics, Chalmers Institute of Technology
Prof. C.G. Granqvist, Ångström Laboratory, Uppsala University
Prof. D. Haviland, Nanostructure Physics, KTH
Prof. Mats Jonson, Göteborg University
Prof. Ulf Karlsson, Materialfysik, KTH
Dr. Lazlo Kiss, Ångström Laboratory, University of Uppsala
Dr. Mirka Mikes-Lindbäck, ABB Corporate Research
Prof. Nils Mårtensson, MAX-Laboratories, Lund University
Prof. Arne Rosén, Department of Physics, Chalmers Institute of Technology
Prof. J. Roeraade, Dept of Analytical Chemistry, KTH
Prof. Lars Samuelson, Dept. of Solid State Physics, Lund University
Dr. Steven Savage, FOA (National Defense Research Institute)
Prof. Mats Wilander, Dept of Physics, Univ. of Göteborg/Chalmers

Background

The WTEC team's site visit to Sweden was greatly facilitated by Prof. Rao and Prof. Muhammed, who kindly organized a one-day workshop at the Royal Institute of Technology (KTH) in Stockholm. Groups from across Sweden involved in nanoscale science and technology were invited to send representatives to participate in this workshop. Representatives from the Royal Institute of Technology, Uppsala University, Chalmers University of Technology, Göteborg University, and Lund University, together with program managers from four of the funding agencies in Sweden, contributed to the workshop.

Sweden has made a conscientious effort to have broad-scale information exchange in the area of nanoscale science and technology. There are several consortia (described below) that not only have a multidisciplinary composition but also multiorganizational composition in most instances. As examples, in the area of mesoscopic (20 Å < size < 500 Å) physics, 80-100 people are involved from various institutions in Sweden, and the Nanometer Structure Consortium at Lund has on the order of 100 people involved. Regular meetings are held by the National Board for Industrial and Technological Development (NUTEK) Competent Centers, and the scanning probe community has regular meetings for researchers throughout the country.

Presentation of Consortium Efforts

After introductory comments, which included a welcome from Prof. Ingmar Grenthe, the Vice President of the Royal Institute of Technology (KTH), overviews of four major consortia in the Nanoscale Science and Technology area were presented:

1. Clusters and Ultrafine Particles, presentation by Prof. Nils Mårtensson of Lund/Uppsala, the consortium leader
2. Nanometer Structure Consortium, presentation by Prof. L. Samuelsson of Lund University, the consortium head
3. Nanophase Materials Consortium, presentation by Prof. M. Muhammed, of the Brinell Center at KTH
4. Ångström Laboratory, presentation by Prof. C.G. Granqvist and Dr. L. Kiss of Uppsala University

These general consortia overviews demonstrated that significant effort is being expended in nanoscale science and technology throughout Sweden. In addition, there either is or is expected to eventually be, substantial industrial involvement in every consortium. Academia's strong and close ties to the industrial needs of Sweden were repeated several times during the workshop.

Reports on the Consortia

1. Consortium on Clusters and Ultrafine Particles

The Consortium on Clusters and Ultrafine Particles is one of the consortia that makes up the Interdisciplinary Materials Research Consortium (see Table C.I) sponsored by the Swedish Foundation for Scientific Research (SSF), the Natural Sciences Research Council (NFR), and NUTEK. The present Consortium leader is Nils Mårtensson, who is also the new Director of MAX-Lab, the synchrotron facility at Lund. The three primary areas of focus of this consortium are (1) catalysis (clusters – nanophase materials), (2) nanostructured electrodes, and (3) hard materials.

The consortium consists of groups from several different universities and disciplines that collaborate in this area. For example, participants include Uppsala researchers from Physics in Surface Science, Liquid ESCA (electron spectroscopy for chemical analysis), Quantum Chemistry, and Dynamic Electrochemistry; University of Stockholm researchers from Physics in Theory; Linköping researchers in Theory of Spectra; and KTH researchers in Materials Chemistry and Ceramics. In addition there are strong interactions with industrial researchers.

Examples of research being carried out in this consortium are investigations of the fundamental properties of CO dissociation on supported metal clusters. XPS studies of the energy shift in the carbon 1s line have allowed investigators to follow CO dissociation on different nanosize rhodium clusters and conclude that clusters containing on the order of 1,000 rhodium atoms supported on alumina were the most adept at dissociating CO. Clusters containing both less and more rhodium dissociated a much smaller fraction of the CO. Similarly, bonding of organic acids on metals, e.g., formate and acetate on Cu(110), is being studied experimentally by XPS and modeled by theory.

These experiments are made possible by the use of the synchrotron radiation at MAX-lab, which is located at Lund University. The MAX-II is a third-generation facility, which means that it has been optimized for insertion devices (straight sections). The high intensity X-ray sources at MAX-lab have opened opportunities for X-ray lithography work in two areas that lab researchers are calling micromachining/LIGA process or nanostructuring/IC technology. Potential applications in micromachining include neuro chips, microactuators, microsensors, pressure senders, microparts, filters, flow meters/controllers, and fiberoptics connectors. Potential applications in nanostructuring are sub-0.13 μm microlithography, high speed FETs, biomaterials, fibers and particles, bioelectric sensors, binary diffraction optics elements, optical elements based on CGHs, and high aspect ratio nanostructures.

Another example is the MAX-Lab work on nanostructured semiconductor electrodes for photovoltaics, photoconductors, sensors, electrocatalysis, photocatalysis, electrochromism, electroluminescense, and batteries. The Graetzel cell, which uses particles with controlled morphology, allows optimization of devices that produce electrical energy from light.

2. Nanometer Structure Consortium

During the Stockholm workshop, Prof. Lars Samuelson presented an overview of the organization and work being carried out at the Nanometer Structure Consortium. Since this consortium is reviewed in detail at the end of Appendix C by Evelyn Hu, who separately attended a mini-workshop at Lund Luniversity on 14 October 1997, a separate overview of Prof. Samuelson's presentation is not given here.

3. Nanophase Materials and Ceramics Thematic Network at KTH

The Nanophase Materials and Ceramics Thematic Network is based at KTH and is part of the Brinell Centre. It was established in 1996/1997 and is funded by the SSF, KTH, and by participating industries. Prof. Mamoun Muhammed is project leader of the Nanophase Materials and Ceramics Thematic Network.

The Brinell Centre is a newly formed strategic research center coordinating research in materials science in the Stockholm area. The Brinell Centre performs interdisciplinary research and graduate education in materials science, with a focus on advanced engineering materials. It consists of 15 departments and institutes, mostly based in the Stockholm area. The Brinell Centre represents a very broad spectrum in materials science, ranging from basic physics and chemistry to industrial applications of materials science. One type of advanced material is based on nanomaterials. The center maintains a close relationship with both materials-producing and materials-consuming industries. Graduate students will spend at least 6 months work within an industrial company and accomplish a part of their thesis in work at the company.

The research programs at the Brinell Centre are organized within two *Interdisciplinary Research Programs* entitled (a) Computational Materials Science and Engineering, and (b) Precision Processing of Clean Steels; and three *Thematic Networks* entitled (a) Nanophase Materials and Ceramics, (b) Materials Science for High Temperature and Aggressive Environments, and (c) Surface Science and Coating Technology. The Thematic Networks cover large scientific areas that are also reflected in the graduate school program.

Thematic Network A: Nanophase Materials and Ceramics

This thematic network encompasses the groups of about six professors in the KTH. Nanophase materials are defined here as materials with a grain size in the 1-100 nm range and are found to exhibit greatly altered mechanical properties compared to their normal, large-grained counterparts with the same chemical composition. For example, nanophase materials are up to five times harder than the normal materials. This thematic network focuses on fabrication and evaluation of the mechanical properties of alumina-based composites containing TiC and TiN nanoparticles. The project aims to study the enhancement of the mechanical properties of alumina composites by dispersion of nanoparticles of titanium carbide and titanium nitride. Scanning probe techniques are commonly used to study the interfaces and fabrication of alumina-based composites. Their mechanical properties are evaluated by nano-indentation, and then the indentation areas are mapped in order to better understand the mechanisms leading to improved mechanical properties of bulk alumina by nanoparticles. Another area of interest involves study of cerium oxide catalysts. Studies have shown that significant improvement in the oxygen storage capabilities of these materials has been achieved with neodymium, calcium, lead, or manganese doping. The program is funded "quite handsomely" by industry. For aerospace applications, nanogranular thermoelectrics based upon opals are being studied in collaboration with Allied Signal Corporation.

4. The Ångström Laboratory

The Ångström Laboratory is located at Uppsala University. It is a center in which expertise in materials science has been gathered together from diverse fields of chemistry, materials science, physics, electronics, etc. The facilities have been designed to expedite high technology research and there are specially equipped laboratories to offer optimal conditions for experiments, for example, rooms with extremely high air purity that are free from vibration. Four strategic research programs have been established at the Ångström Laboratory: the Center for Advanced Micro-Engineering, the Ångström Solar Center, the Batteries and Fuel Cells for a Better Environment Program, and the Energy Systems Program.

As an example of the lab's world-class capability is its recent purchase and installation of a $1 million apparatus to fabricate large quantities of ultrafine particles. The apparatus can be operated in several different modes, such as Gas Evaporation Mode or Direct Gas Deposition Mode, depending on the material to be fabricated. The equipment will allow researchers to produce high purity, nearly perfect nanocrystals with a narrow size distribution (2-3 nm in diameter) at a very high production rate (20 gm/hr). Several types of nanoparticles are being produced and examined by different researchers. These include active metal particles, isolated metal particles, nanochains of ferromagnetic nanoparticles, and ceramic nanoparticles. Studies include fabrication of Fe-Ag films for experimental investigation of giant magnetoresistance (GMR) properties, as well as use of "ordinary" nanoparticles to fabricate films from nanopaste for studies of their electrical and thermal resistivity properties.

Reports from Funding Agencies of Sweden

In addition to presentations overviewing consortia efforts, four presentations were given by managers from four different Swedish funding agencies describing nanoscale science support in their respective agencies. Summaries of these presentations follow.

NUTEK

Dr. H. Hakansson stated that NUTEK budgets are being reduced to about SKr. 26 million for 1998, whereas over 50 applications have been received that request support in the amount of SKr. 150 million. NUTEK nanoscale program areas are (a) active materials and nanofunctional materials; (b) microsystems technology; and (c) peripherals.

Natural Sciences Research Council (NFR)

The Natural Sciences Research Council presentation by Dr. U. Karlsson emphasized that the NFR primarily supports basic research. The budget for physics is about SKr. 82.5 million, of which about 25% is for condensed matter physics. It was estimated that about 20-30% of the total NFR chemistry and physics budget supports nanoscale science initiatives, continuing the NFR history of strongly supporting nanoscale science efforts. It supports the Materials Science Consortia, of which the Nanometer Structure Consortium and the Clusters and Ultrafine Particles Consortium are part, and it also supports the National Facility at Göteborg University, which consists in part of experimental physics groups from Lund, Göteborg, Uppsala, Stockholm, and Umea Universities. Interestingly, the NFR also supports “senior research positions.” At present it provides support for positions in the following areas: low dimension structures, mesoscopic physics, surface chemistry, and theory (4 positions). Two other positions are presently under consideration, one in cluster chemistry and another in the physics of small structures.

Swedish Foundation for Strategic Research (SSF)

The Swedish Foundation for Strategic Research is a relatively new organization, created in January 1994 with a SKr. 6 billion budget. As described by Dr. Marika Mikes-Lindback, the goal of the foundation is to support scientific, technical, and medical research. One objective is to build up competence in a field and then get companies founded to commercialize products in that field. Projects are 100%-funded by SSF. There are six main programs, of which five are vertically oriented and one (Materials) is horizontally oriented. Two programs have large components of nanoscale science and technology:

Interdisciplinary Materials Research Consortia, receives about SKr. 42 million in support, about 25% of that for projects involving nanoscience. Table C.1 lists the Interdisciplinary Materials Research Consortia, together with their objectives and 1998 funding levels.

TABLE C.1. Sweden's Interdisciplinary Materials Research Consortia & 1998 Funding Levels

Consortium Leader	Objectives	1998 SKr (M)
Ångström Consortium Soren Berg	Methods and processes for preparation of surface coatings with controllable structure and composition	5.9
Thin Film Growth Lars Hultman	Growth of thin films for power electronics, for magnetic multilayers, and for wear-protective coatings	6.3
Nanometer Structures Lars Samuelson	Nanometer structures and their applications; fabrication and characterization	5.5
Clusters and Ultrafine Particles Nils Mårtensson	Physical and chemical methods for synthesizing and characterizing clusters and ultrafine particles	3.3
Biomaterials Bengt Kasemo	Physics and chemistry of surfaces and their interaction with biological systems	5.7
Theoretical and Computational Materials Physics Bengt Lundqvist	Theoretical and computer-aided methods and models and application to technologically relevant materials	4.7
Computer-Assisted Materials and Process Development Bo Sundman	Creation of a computer-based tool for materials and process development	4.1
Superconducting Materials Tord Claeson	Thin film HT_C materials preparation and characterization and optimization of their properties and applications	5.7

High Speed Electronics, Photonics, and Nanoscience/Quantum Devices receives SKr. 40 million in support, of which ~ 25% is targeted for nanoscience. This program is being established because Sweden believes that the microelectronics area is highly strategic for modern society and affects all sectors of industry as well as the information society generally. Its primary goal appears to be to open the pipeline to a continual supply of well-trained and -educated researchers to industry. It is a joint strategic research program and graduate school at the Royal Institute of Technology (KTH), Chalmers University of Technology and Göteborg University (CTH/GU), and at Lund University (LU). The joint program is based on three research proposals submitted by CTH/GU (Components for High Speed Electronics), LU (Nanoscience) and KTH (High Speed Electronics and Photonics), all of which are judged to have current relevance to the Swedish microelectronics industry. The goal of the joint program is to "create research results within these research sub-fields, but specifically also to create novel ones by a strategic cooperation within and between the sub-fields and Swedish electronics industry." The goal of the graduate school is to "provide Ph.D.s and Licentiates with a education which fulfills both the short term and the long term needs of the Swedish society and in particular the Swedish industry." After the initial four-year startup period, students will be graduating at a rate of 15 per year, with 80% going to industry.

Defense Research Establishment (FOA)

The FOA is Sweden's national defense research establishment. It has about 1,000 employees and an annual budget of SKr. 600 million. The defense research must function as a link between the possibilities offered by science and technology and the needs of the armed forces of Sweden. Dr. Steven Savage of the FOA's Department of Materials gave a presentation entitled "Nanostructured Materials at FOA." There has been a proposal presented to FOA to free up about 3% of the organization's funds for nanoscale research programs. At present, there are only some small efforts that involve nanoscale materials within existing projects:

- molybdenum, chemical precipitation, and dynamic consolidation
- additives to new explosive compounds, e.g., aluminum or iron oxide particles
- high-strain-rate properties of nanostructured aluminum alloys
- coating 50 µm particles to create energetic materials with conducting layers
- fullerenes as optical limiters for laser protection

In an attempt at international collaboration, the FOA is participating in an EU project application for fabrication and study of nanostructured light materials. The coordinator of this project is Prof. Brian Cantor of Oxford University.

Individual Presentations from Research Groups

The last part of the workshop at KTH was devoted to presentations from individuals who gave brief overviews of the nanoscale science and technology research efforts in their individual groups.

Prof. David Haviland, now at KTH, described his efforts in nanostructure physics. He uses lithographically defined nanostructures to study electronic transport phenomena such as Coulomb blockage, spin-dependent transport, and theory involving quantum optics in nanostructures and diffraction optics in nanostructures. Prof. Haviland collaborates closely with Profs. P. Delsing and T. Cleason of the Single Electron Group at Chalmers.

Prof. K.V. Rao of KTH described his group's research in large scale applications of soft magnetic materials. The work is entitled Functional Nanometric Science and consists of three primary thrusts:

1. Production by several different techniques such as thin film deposition using rf laser ablation, rf sputtering, and e-beam deposition; rapid solidification technology such as melt spinning to produce GMR materials; and chemical co-precipitation techniques.
2. Characterization using surface probe microscopy; atomic force, scanning tunneling, and magnetic force microscopy (AFM, STM, and MFM) are key techniques.
3. Applications of nanostructures, under study as magnetic dots, novel GMR materials, high T_c-based tapes from nanosize precursors, nanolithography and carbon nanotubes and fullerenes as nanoscale electrodes.

Prof. Arne Rosén of Chalmers University of Technology and Göteborg University presented a detailed overview of the nanoscale science being carried out in his Molecular Physics Group. The title of his talk, "Clusters, Fullerenes, Nanotubes and Nanowires: New Building Blocks in Nanoscience," accurately describes the presentation. A brief description of the key areas of interest is given here. The key research areas in his group cover six main themes:

1. surfaces and catalysis
2. metal clusters
3. fullerenes and nanotubes
4. combustion engine research (there is a center dedicated to this work)
5. medical-related research
6. related other projects

Two areas that are almost entirely devoted to nanoscale work are the metal cluster and the fullerene and nanotube research areas. In both areas there is a strong experimental effort, coupled with a strong theoretical effort.

For example, the metal cluster experimental approach is directed towards studies of reactivity and electronic properties of free (molecular beam) metal clusters and studies of size-selected deposited metal clusters. The theory then examines electronic structure of free metal clusters, calculations of electronic structure for adsorbates on clusters, ab initio molecular dynamics (MD) calculations of clusters and adsorption on clusters, MD simulations of thermal properties, and simulations of cluster atom collisions. The approach taken in this group closely ties experiment to theory, as well as basic science to applied science.

Prof. Bengt Kasemo oversees nanoscience research that consists of three main thrusts:

1. Nanofabricated model catalysts. In this thrust, modern micro- and nanofabrication methods are used to provide a new avenue to prepare controlled model catalysts that are expected to realistically mimic real supported catalysts. These catalysts consist of 2-D arrays of active catalysts deposited on active or inactive support materials. Particle size, shape, separation, and support can be systematically varied. The structures are easily accessible to scanning probe imaging and surface analysis techniques. The 2-D analogs of supported catalysts are illustrated by Pt particles in the size range 10-500 nm deposited on alumina and ceria manufactured by electron beam lithography. The sintering mechanisms of Pt particles on support materials and the role of oxygen supplied from support material (e.g., ceria) in catalytic reactions are being studied.
2. Nanofabricated metal particles. Nanofabrication is used to create arrays of Ag particles of 100-200 nm in size and of different shapes in order to study the influence of these parameters on the ability to detect individual biological molecules using surface enhanced Raman spectroscopy. Kasemo's group has successfully shown this for colloidal Ag suspensions (3-D) as well as 2-D arrays of nanofabricated Ag particles made by electron beam lithography.
3. Colloidal lithography for biomaterials applications. Different methods are being explored to create surfaces of interest for biomaterials testing and applications by using large area topographic patterning of nanoscale features by colloidal lithography (8-200 nm). Specifically of interest is how nanometer-scale topography influences biomolecule and cell adhesion and function at surfaces.

Prof. Tord Claeson described the work in Nanoelectronics, Nanoscience at Chalmers University of Technology. Approximately 100 people are involved in this research effort. The main areas of interest are in high electron mobility transistors, electron hole drag phenomena, fabrication of junctions with small capacitance, phase coherent transport with possible applications to superconducting mirrors, and biological applications in which they have shown that nanoscale TiO_2 fibers are engulfed by cells without cell collapse, whereas silica fibers cause cell collapse.

Prof. Mats Jonson overviewed the theoretical efforts at Göteborg University. About 15 theorists are involved in study of mesoscopic systems. Efforts are directed towards theoretical understanding of phase coherence in mesoscopic systems, strong electron correlation effects, nonequilibrium situations, high frequency microwave response, and mixed metal superconducting materials.

Summary

In the general discussion at the end of the workshop, the following themes were emphasized:

- In Sweden there is a good and close relationship between experiment and theory. Most groups or programs have a strong experimental as well as theoretical component.
- There is a strong sensitivity towards industry. Industry in Sweden puts money into development but not so much into research. One comment was that there are too few people with PhD-level education in industry. Programs were described during the workshop where this is being addressed.
- Large industrial firms in Sweden appear to be more closely coupled to the academic community in the universities than are smaller firms.
- Most technical research in Sweden is carried out in universities. Sweden does not have an institute/ national laboratory organization equivalent to that in some other countries.
- Nanoscale research is of interest to several industries, such as those interested in ceramics, powder metallurgy, thin films, electronics, magnetic materials, catalysis, and energy storage.

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WTEC panel co-chair Evelyn Hu participated in a mini workshop at the University of Lund at which several scientists made presentations on their work, some working within the Nanometer Structure Consortium there, and some working in academia and industry at other locations.

This consortium, based at Lund University, was initiated about 1990. The Coordinator is Professor Lars Samuelson of Lund. It primarily involves the Lund University Solid State Physics group, although the interaction encompasses other departments at Lund, as well as collaborators at other universities such as Chalmers. Having a 10-year lifetime, the consortium is primarily funded by the Natural Sciences Research Council (NFR), and the National Board for Industrial and Technological Development (NUTEK). The consortium is guided by an Advisory Board, which includes industrial members and academic leaders both from Sweden and from other countries. The Chair of the Advisory Board is from industry. Industrial participation is considered important, and Lund hosts an adjunct Professor from Ericsson, who spends 20% of his time at the university, advising students and student projects. The very strong industrial support and commitment is believed to be linked to Swedish industry's recognition of the importance of long term research carried on within the universities. In addition to the funding from NFR and NUTEK, the consortium receives funding from the Research Council for Engineering Sciences (TFR) and also participates within ESPRIT programs, funded by the European Union.

As a point of interest, the graduate student population in this area is *not* diminishing in Sweden, as is true in many other countries. Part of the reason may lie in the fact that graduate students are given stipends, which are designed to be competitive with what MS students would be paid in industry (total funding for students is collected from grants, the university, and the government). Another factor may be that industry hiring of PhD students has been more stable than in other European countries.

The consortium seems well equipped, having moved into new, expanded facilities in 1983. There are small clean room spaces for TEM and e-beam writing, extensive growth capabilities (gas source MBE, CBE), a newly installed ultrahigh vacuum chemical vapor deposition system for growth of silicon-based materials, and a host of characterization tools: micro PL, atomic force microscopy (AFM), and low temperature, high magnetic field apparatus. A highlight of the program is synthesis of aerosol particles (metals, subsequent conversion to semiconductors: GaAs, InP) with size selection, and the use of AFM manipulation to controllably position the particles. The consortium also makes use of the on-site synchrotron source, MAX-Lab, a national (and international) user facility that has recently brought up a larger, brighter ring that will be used for X-ray lithography, surface studies, and structure studies for biological samples.

The consortium held its annual review on the 13th and 14th of October, with a mixture of invited talks from outside speakers, and talks and posters presented by the consortium students. The invited speakers included Dr. Suhara from Tokyo Institute of Technology and Professor Fukui of Hokkaido University. Both researchers are carrying out joint projects with the consortium. Among the invited speakers were the following:

Thomas Lewin from Ericsson Microwave Systems offered an industrial perspective on quantum nanoelectronics, pointing out that although he could not give an answer to “what would nanoelectronic devices be used for,” that 50 years ago, one could hardly have predicted the current importance of the transistor. He noted that in 1948, at the time of invention of the transistor, the primary “high tech” companies were major vacuum tube suppliers such as GE, RCA, and Philco. Within ten years, catalyzed by the invention of the transistor, dominance of these companies had been ceded to Motorola, Texas Instruments (which had formerly specialized in geophysics), and Fairchild (which had formerly specialized in camera and instrumentation for air surveys).

Lewin noted the importance and pervasiveness of Moore’s Law, and how the transistor has been the pacesetter for technological development; whether we are prepared or not, the scaling down of current technology will place us in the “Nano Era” by about 2010 or so, and we should be prepared for it (Fig. C.1).

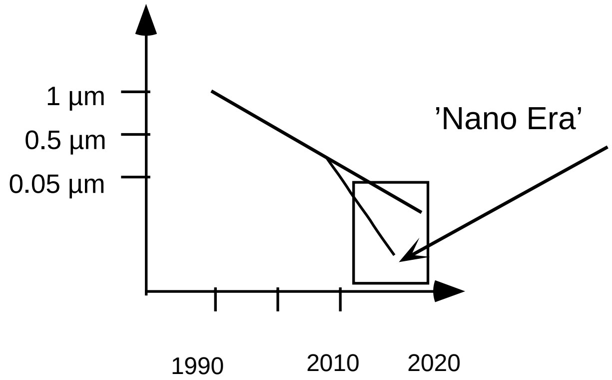

Figure C.1. Moore's Law in the "Nano Era."

Another interesting talk and industrial perspective was given by Dr. Sandip Tiwari of IBM, who spoke on "Nanocrystal and quantum-dot memories." His plan is to integrate and take advantage of silicon quantum dots in a more natural way, within the context of "mainstream" silicon electronics. This would entail the controlled and discrete charging of nanodots, placed immediately above a gate oxide in a MOS device, as a means of controlling the source to drain current, with an enormous gain in output compared to input signal. His claim is that such an application can operate at room temperature, integrate and enhance a dominant technology, and not suffer from many of the drawbacks of nanodots, such as long charging/access times and variations in dimension.