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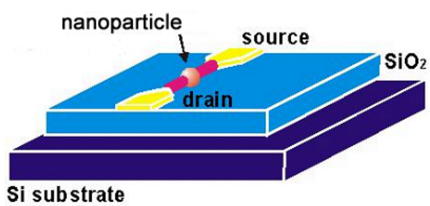
Biologically Templated Assembly of Nanoscale Electronic Devices

Brendan Manning, Andrea di Silva, Sarmiza Stanca and Donald Fitzmaurice*
Department of Chemistry, University College Dublin, Belfield, Dublin 4, Ireland

The demand for integrated circuits that will allow information be processed at even faster speeds remains undiminished. This is despite the fact that, as a result of miniaturization, the density of the wires and switches that comprise such circuits has doubled every eighteen months giving rise to Moore's Law [**1**]. While it is expected Moore's Law will hold true until 2016, it is not expected that it will hold true thereafter for two reasons [**2**]. The first reason is that to build smaller wires and switches requires major advances in the established fabrication and materials technologies. Specifically, it requires the development at great cost of new light sources and process tools; new mask and resist materials; and new high and low dielectric constant materials. The second reason is that as wires and switches become smaller the materials of which they are composed no longer exhibit bulk properties, but exhibit properties dominated by confinement and surface effects.

The responses of the related scientific and engineering communities have been two-fold. The first response has been to develop alternative fabrication technologies. The second response has been to propose new integrated circuit architectures that can accommodate or even exploit the novel properties exhibited by these smaller wires and switches. When contemplating alternative fabrication technologies, one is immediately attracted to the self-assembly in solution and self-organization at a conventionally patterned silicon wafer substrate of nanoscale wires and switches [**3**]. When contemplating alternative materials technologies, one is immediately attracted to the use of supermolecules and biomolecules as templates and modified nanoparticles and nanorods as building blocks [**4**,**5**]. It is noted, that there have been a number of recent reports that have demonstrated the potential of these and related approaches [**6**-**10**].

It is in this context, that we have recently reported the DNA-templated assembly of a protein-functionalized 10 nm gap electrode on a silicon wafer substrate from suitably modified gold nanoparticles [**11**]. We have also reported the recognition-directed assembly of a suitably modified gold nanoparticle in to this gap. The resulting model device is shown below. Currently we are focusing on establishing and optimizing the electronic properties of this device [**12**].



The next challenge is to organize the DNA templates used to assemble this and similar nanoscale devices between the electrical contacts found on a patterned silicon wafer substrate. In this context we will describe our most recent work directed at the combined use of conventional and chemical lithography to pattern arrays of electrical contacts on silicon wafer substrates and to pattern chemical binding sites in the gaps between these contacts. Specifically, we will describe the preparation of nanometer gap electrical contacts, where the surface of the silicon wafer has been modified by adsorption of a monolayer of an aromatic nitro compound. Following irradiation of the wafer through a mask, the above monolayer is converted to an aromatic amine in the gap between the contacts [**13**]. The irradiated regions of the silicon wafer substrate, following further chemical modification of the amine, recognize and bind selectively the DNA templates used to assemble the nanoscale devices and to localize them between the above contacts. This and related work in our laboratory is focused on the strategic goal of organizing bottom-up nanoscale devices on top-down patterned substrates. Such hybrid strategies will be important in the medium term and will pave the way for entirely bottom-up approaches in the future.

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Nanotechnology in the Fraunhofer Microelectronics Alliance (VµE)

B. Fischer[1], L. Frey[1], L. Pfitzner[1], J. Lorenz[1], H. Ryssel[1], P. Kücher[2]

[1] Fraunhofer Institute of Integrated Systems and Device Technology (IISB), Erlangen, Germany
[2] Fraunhofer Center of Nanoelectronic Technologies (CNT), Dresden, Germany

The German Fraunhofer Microelectronics Alliance (VµE) conducts applied R&D in the field of micro and nanoelectronics in a very broad range, from leading edge research over manufacturing issues to specific applications. Working in close collaboration with industry, the VµE consists of 10 institutions with a staff of 1500, including the Fraunhofer Center of Nanoelectronic Technologies (CNT), a new private-public partnership with AMD and Infineon to be established in spring located close to their 300mm manufacturing lines in Dresden. Within the VµE, nanotechnological applied research in the field of front-end technologies, focussing on new materials, alternative structuring techniques, and manufacturing is carried out by the Fraunhofer Institute of Integrated Systems and Device Technology (IISB), Erlangen. The Fraunhofer Institute of Reliability and Microintegration (IZM), Berlin, covers the whole field of back-end, and the Fraunhofer Institute of Photonic Microsystems (IPMS) in Dresden is dealing with nanophotonics. The VµE puts special emphasis on its unique transfer chain concept: e.g. front-end technology investigated at Fraunhofer IISB can be transferred with a high level of efficiency for short development cycles into Fraunhofer CNT as the platform for manufacturing implementation. This poster presents the VµE and its nanotechnological capabilities as a powerful European research network and international partner.

Contact:
Dr. Bernd Fischer
Fraunhofer Institute of Integrated Systems and Device Technology (IISB)
Schottkystrasse 10
91058 Erlangen
Germany
Phone: +49-9131-761-106
Fax: +49-9131-761-102
E-Mail: bernd.fischer@iisb.fraunhofer.de

Nanoelectronics at the Fraunhofer IISB and the University in Erlangen

J. Lorenz[1], L. Frey[2], L. Pfitzner[1], H. Ryssel[1,2]

[1] Fraunhofer Institute of Integrated Systems and Device Technology (IISB), Erlangen, Germany
[2] Chair of Electron Devices, University of Erlangen-Nuremberg, Erlangen, Germany

Within the Fraunhofer Microelectronics Alliance, the Institute of Integrated Systems and Device Technology IISB focuses on R&D for front-end silicon technology, together with the Chair of Electron Devices LEB of the University of Erlangen- Nuremberg. This extremely close cooperation is highlighted by joint forces in terms of management and use of cleanrooms and equipment. It is an excellent example for the successful role of Fraunhofer to link academic research and education on one hand side, to applied industrial development on the other hand side, and is unique for the field of nanoelectronics within Germany. This is complemented by a large network of cooperations between IISB and LEB and many companies and research establishments throughout Europe and beyond, among others within compound research projects funded by the European Commission and frequently coordinated by IISB, especially in the area of process simulation. The poster will show some highlights of results obtained e.g. in the areas advanced dielectric layers, ion beam processing, nanometrology, Advanced Process Control, alternative lithography, nonvolatile memory concepts, simulation of dopant diffusion/activation and of optical lithography, and 3D process simulation in general, including its application to the study of advanced device architectures.

Poster Abstract Submission for INC1, San Francisco, June 1-3, 2005
Contact:
Dr. Jürgen Lorenz
Fraunhofer Institute of Integrated Systems and Device Technology (IISB)
Schottkystrasse 10
91058 Erlangen
Germany
Phone: +49-9131-761-210
Fax: +49-9131-761-212
E-Mail: juergen.lorenz@iisb.fraunhofer.de

Fraunhofer Nanotechnology Beyond Electronics: Making small things effective

J. Lorenz[1], K.-H. Haas[2]

[1] Fraunhofer Institute of Integrated Systems and Device Technology (IISB), Erlangen, Germany
[2] Fraunhofer Institute of Silicate Research (ISC), Würzburg, Germany

Nanotechnology is a cross-cutting technology, which leads to breakthroughs in many areas of science and engineering, such as microoptics and -electronics, materials, biotechnology, process engineering and measurement tools. For all these areas the mastering of effects on the nanoscale offers large prospects for improved and new processes, products and tools. In the Fraunhofer nanotechnology initiative 17 institutes from almost all application areas of Fraunhofer share the vision to combine their expertise and forces to investigate and master nanoscale effects. Currently guiding themes are: The application of multifunctional coatings useful in e.g. the automotive industry, the design of special nanoparticles as carriers for applications in biotechnology or medicine and the use of carbon nanotubes as actuator materials. In this poster, scope and partners will be presented together with typical results for all areas of nanotechnology where Fraunhofer is active.

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Contact:
Dr. Jürgen Lorenz
Fraunhofer Institute of Integrated Systems and Device Technology (IISB)
Schottkystrasse 10
91058 Erlangen
Germany
Phone: +49-9131-761-210
Fax: +49-9131-761-212
E-Mail: juergen.lorenz@iisb.fraunhofer.de

Nanocircuits

Josef Sauerer, Günter Elst, Hans Hauer
Fraunhofer Institut for Integrated Circuits

Abstract:

Nanotechnology research currently mainly concentrates on technology development yielding smaller and smaller transistors and new devices. This leads to potentially extremely high integration densities. But in order to exploit this potential new approaches are necessary to bridge the architectural gap as well as the physical gap. The Fraunhofer Institute for Integrated Circuits IIS is about intensifying basic research on modelling, design tools, and design methodologies as well as on circuit technologies for nanotechnologies.

The modeling of devices including parasitic effects leads to multi domain models with electrical, electromagnetic, thermal, and mechanical components. These models are the base for investigations of the influence of the technology features on the circuit and system behavior and for development of new design methods.

The challenge in physical design (especially for analogue circuits) will be to develop circuit techniques which are robust against technology parameter and device variations. The circuits must work with extremely low voltage headroom and nevertheless provide a reasonable signal dynamic and signal integrity with noisy devices. Leakage currents have either to be suppressed or controlled to avoid thermal crashes and provide reasonable operating times for portable devices. These circuit architectures are initially conventional CMOS technology based but will more and more exploit new nanodevices.

Molecular Engineering of Polymer / Carbon Nanotube Composites

Prof. Werner J. Blau, Physics Department, Trinity College Dublin, Ireland

Since the discovery of carbon nanotubes (CNTs) in 1991, researchers have envisaged potential applications such as nanoscale electronic circuits, bio/medical nanomaterials, and the construction of complex carbon-based nanodevices. Thus, the assembly of basic building blocks of complex nano-architectures, e.g. conjugated polymers and nanotubes, has been a driving force of much of the nanoscience community. A first step toward realizing this goal may be the attachment to, or modification by carbon nanotubes of structures such as polymers. This leads to the possibility of assembling individual polymer molecules onto carbon nanotubes with the net effect being the modification of the polymer's physical properties and electronic structure in a predictable way.

For this talk, I have chosen a number of examples from vastly different applications areas to demonstrate the enormous potential of this concept and the resulting new class of nanomaterials.

The assembly of polymers into a well-defined nanometric coating around CNTs will be described. Using scanning tunnelling microscopy and scanning tunnelling spectroscopy we demonstrate that the low energy electronic structure of the assembled material is dominated by the one-dimensional nature of the nanotube as reflected in van Hove singularities. We report physical 'doping', to use the traditional term, using small concentrations of multiwalled nanotubes in PmPV in a polymer/nanotube composite. This can increase electrical conductivity of the polymer by up to ten orders of magnitude. The nanotubes also act as nanometric heat sinks, preventing the build up of large thermal effects, caused either optically or electrically.

CNTs are also a potential exceptional reinforcement material for polymers. It is well known and reported that CNTs have outstanding mechanical properties such as Young's modulus of 1-2TPa and tensile strength of up to 60GPa. It is of immense importance to insure a good dispersion of CNTs in the polymer matrix as well as a strong interfacial bonding between CNTs and the polymer chains. This is essential in order to insure that the applied load is carried by the reinforcement agent rather that by the polymer matrix. For example, it may often be necessary to covalently attach nanotubes to surfaces or molecules or to functionalise nanotubes with units such as polymers. In this talk, it will be shown that the mechanical reinforcement of polymer composites using carbon nanotubes is dependant on the total surface area of carbon nanotubes dispersed into the polymer matrix. Several differently produced CNT samples were introduced into a polyvinyl alcohol matrix and the sample with the smallest diameter, thus the nanotube sample with the highest surface area, increased mechanical properties such as tensile modulus by 120% while adding less than 1wt% of carbon nanotubes.

We have also been investigating the use of a conjugated polymer (P*m*PV) and carbon nanotube composite as an electron transport / hole blocking layer in polymer light-emitting diodes and solar cells. At all nanotube to polymer mass ratios used for the composite, the relative efficiencies for the devices using this material have been improved compared to the M*3*EH-PPV single layered devices. We observe an optimum in the relative efficiency for a mass ratio of 8%.

Finally, we have observed a substantial nonlinear optical response including ultrafast near-infrared degenerate four-wave mixing, multi-photon absorption induced luminescence from quantum confined states, and extraordinarily efficient optical limiting action.

Nanomaterials for Organic Photonics Applications

Prof. Werner J. Blau, Physics Department, Trinity College Dublin, Ireland

Organic and polymeric materials offer a unique range of tailoring optical properties through control of morphology on the nanometer scale. This contribution will explore a range of different material systems such as carbon nanotubes, templated metal nanorods and self-assembled molecular nanowires in different photonic scenarios. Applications to be discussed include optical limiting, fibre lasers, polymer light emitting diodes and solar cells.

Optical limiters are materials that strongly attenuate intense optical beams while exhibiting high transmittance for low-intensity ambient light levels. They are of significant interest for the protection of human eyes, optical elements, or optical sensors from intense laser pulses, as well as having potential application in the field of optical switching.

Phthalocyanines and Fullerenes are materials that optically limit via a nonlinear absorption process at 532 nm (i.e. Nd:YAG second harmonic) laser irradiation. The absorption mechanism in these compounds is population of excited states through multi-step nonlinear absorption, leading to Reverse Saturable Absorption. Phthalocyanines offer a tremendous architectural flexibility in structure. Attaching peripheral groups to the main macro-cycle, the attaching of metals in the central cavity and subsequently attaching axial substituents to that central metal, can modify the basic structure and thus this allows tailoring of the response of the molecular unit. We have measured over 50 different Phthalocyanine molecules to understand underlying molecular engineering principles and explore opportunities for optimizing the response.

Furthermore, we report a method for the fabrication of Phthalocyanine particles with dimensions in the nanoscale regime. We find intermolecular effects to strongly influence the linear and nonlinear optical properties. Linear optical studies, including absorption and emission spectroscopy, are used to investigate the interactions between the molecules inside the particles. The Z-scan technique was employed to examine the optical limiting effects in Phthalocyanine nanoparticles compared to solutions of the corresponding molecules. Transmission electron microscopy (TEM) and atomic force microscopy (AFM) studies were performed to further investigate the particle structure. Furthermore, X-ray diffraction measurements were made to probe the molecular alignment in the nanoparticle.

We have also carried out an experimental linear and nonlinear optical study of single and multi-walled Carbon Nanotubes. Nanotube composites formed with a conjugated luminescent polymer, poly (m-phenylenevinylene-co-2,5-dioctoxy-p-phenylenevinylene) were also investigated. This polymer self-assembles on the nanotubes thus rendering them processable. Nanotubes can increase electrical conductivity of the polymer by up to twelve orders of magnitude without significant loss in luminescence quantum yield. We report electroluminescence from an organic light emitting diode using the composite as electron transport layer in the device. Furthermore, we have observed a substantial third- order nonlinear optical response in the near infrared in thin film samples. Multi-photon absorption induced visible photoluminescence is observed in multi-walled samples.

Activity on Societal Issues of Nanotechnology in AIST

Yumi Negami and Masafumi Ata
Technology Information Department, The National Institute of Advanced Industrial Science and Technology (AIST)
AIST Tokyo Headquarters Office, Annex 10th floor, Ministry of Economy, Trade and Industry 1-3-1 Kasumigaseki, Chiyodaku, Tokyo 100-8921, Japan

AIST is an independent administrative research institution affiliated with the Japanese Ministry of Economy, Trade and Industry (METI). Nanotechnology is one of the most important fields of study at AIST, together with Materials S&T and Manufacturing.

To expedite the public acceptance of nanotechnology, we organized a debate series entitled “Nanotechnology and Society” that aimed to provide a platform for open dialogue on societal issues of nanotechnology, to mobilize a network among researchers and policy makers working for research and strategic fields of nanotechnology, and to present an appropriate policy recommendation at the right time. To ensure transparency, all of the debates are open to public participation and the full debate proceedings are released on our HP.

We also organized a symposium “Nanotechnology and Society” on 1st February 2005. It was the first and comprehensive symposium on societal issue of nanotechnology in Japan that involved many research institutions and ministries including Council for S&T Policy of Cabinet Office.

With the same framework, we are planning a research project on safety and health issue of nanotechnology. All of these activities related to societal issue of nanotechnology in Japan will be presented.

Mesoporous Thin Films in Electronic Nanotechnology

M A Morris[1,2], J D Holmes[1,2], R Rice[2], D Arnold[2] and M Shaw[1,2,3]

[1]Centre for Research in Adaptive Nanostructures and Devices (CRANN)
Trinity College Dublin
[2]Dept. of Chemistry, University College Cork, Cork, Ireland
[3]Intel, Ireland, Leixlip, Co. Kildare, Dublin

Contact M A Morris:
Tel: +353 21 4902180 Fax: +353 21 4274097 e-mail: m.morris@ucc.ie

Abstract
Mesoporous Thin Films (MTFs) are a ceramic matrix through which run ordered arrays of regular pores. They can be developed through relatively simple sol-gel technologies combined with an organic surfactant as a structural directing agent (SDA) or template. The organic component can be removed by extraction or calcination. MTFs are thought to have a number of electronics uses including:- application as ultra-low dielectric constant materials in inter-level dielectrics, 'on-chip' gas sensors, 'on-chip' separation media (i.e. nano-chromatography) and possible intermediates to other important oxide films. We have used these systems as a means to develop regular arrays of high-density nanowires at substrate surfaces.

In this work we summarise some of our important recent results. Methods for producing highly regular MTF films and their characterisation will be outlined and in particular how these films can be controlled by substrate engineering. Summary of the development of nanowires within these systems and some initial electrical characterisation will also be detailed. Finally, we will describe some of the potential benefits of these systems giving recent results of dielectric testing and chromatographic separation as well as describing some of the highly regular nanowires systems that can be developed by use of these systems as templates.

SLM Technology for Microlithography

Ulric Ljungblad[1] and Peter Dürr[2]

[1] Micronic Laser Systems AB, P.O. Box 3141, 18303 Täby, Sweden

[2] Fraunhofer Institute for Photonic Microsystems, Grenzstr. 28, 01109 Dresden, Germany

ABSTRACT

The introduction of Spatial Light Modulators (SLM) provides a possibility for optical mask writers to combine nano-scale resolution and accuracy with short write time for cost effective mask patterning. In the Sigma 7300 mask tool from Micronic Laser Systems AB (MLS) this new technology is implemented where an SLM, developed by the Fraunhofer Institute for Photonic Microsystems (FhG-IPMS), with a million movable micro-mirrors offers advantages not available in other mask patterning tools.

Each micro-mirror on the SLM is individually addressable by means of electrostatic deflection. The analog data matrix is updated with a frequency of up to 2kHz, which gives an 8bit data rate of 2Gbytes per second. The projected pixel size at a demagnification of 200x is 80nm, and analog tilt angles allow an addressing grid of less than 1.5nm at an accuracy of better than 7nm over a whole mask blank (12cm squared).

The SLM is tailor-made for the application in a joint development program between MLS and FhG-IPMS, which started in 1997 where the parties have worked closely together over long time to ensure a high quality product.

Exploiting the electron spin in microelectronics

W. Van Roy, L. Lagae
Imec, Kapeldreef 75, B-3001 Leuven, Belgium
vanroy@imec.be, lagae@imec.be

The electron spin is at the heart of many non-volatile storage applications. Collective behaviour of spins in ferromagnetic metals is used for data storage in e.g. hard-disks. Spin-dependent transport in metallic multilayers is exploited to obtain very sensitive sensors for read heads. Also in semiconductors the spin of charge carriers has a large potential. Until recently this has been largely ignored by the industry, but interest is growing as traditional CMOS scaling becomes increasingly challenging, and alternative routes are being explored.
Highlights of the spin-related research at IMEC that will be presented include:
- Development of a full family of spin-dependent contacts on *non-magnetic* III-V *semiconductors*, the study of electrical injection *and* detection, as well as the transition towards Si and device prospects.
- Development of *ferromagnetic semiconductors* (FMS), where spin-spin interactions may eventually lead to directly spin-based information transfer. The IMEC-lead "FENIKS" research project has resulted in unparalleled understanding and control of the canonical FMS (Ga,Mn)As, world-record Curie temperature for bulk films, novel magnetoresistance results, and highly efficient Zener injectors resulting in 80% spin injection into non-magnetic semiconductors. New semiconductor families are being studied with the aim of increasing the operation temperature.
- The excitation and visualization of magnetostatic spin waves in *ferromagnetic metals*, which may pave the way towards short wavelength spin wave based data manipulation in ferromagnetic metals and semiconductors.
- Observation of interface effects on dissipation of precessional magnetic motion at magnetic/non-magnetic interfaces, which give a first indication towards the existence of spin currents without a net electrical 'charge' current in metallic systems.

300 mm nanoelectronics and other nanotechnology initiatives in Europe

Mehdi Moussavi
CEA-LETI, 17 Rue des Martyrs 38054 Grenoble Cedex 9 FRANCE
mehdi.moussavi@cea.fr

With reference to the analysis of the European Nanobusiness Association (ENA), the most active European countries in the areas of Life Science, Information Society Technologies and Aeronautics and Space will be presented.

The special focus is on Minatec and Nanotec 300 initiative in Grenoble France in close relationship with the semiconductor alliance (STMicroelectronics, Philips and Freescale Semiconductor) in Crolles 2. The huge investments costs are more than each single company can handle. The emerging multicultural organizations can generate mutual benefit for different partners but also imposes a new paradigm for Semiconductor Industry from R&D activity to volume manufacturing in terms of risks, assets and intellectual property sharing. Already a large hub of Nanotechnology activity, Grenoble is poised to be a unique example in Europe in the continuity of Semiconductor related activity from advanced R&D to volume manufacturing. While Crolles 2 plans to start 45 nm early start by the end of 2005, Nanotec 300 is focusing activity on advanced material evaluation and individual process integration for 32-22 nm technology nodes based on

- Widely open Joint Development Projects with equipment suppliers.
- Short loops with Crolles 2 and equipment suppliers.
- Relying on basic research infrastructure (CNRS, University …).

Minatec will enhance this innovation through proximity in gathering in a single campus multicultural research teams on micro- and nanotechnologies, along with education and industry-oriented R&D.

A Process Integrating Carbon Nanotube Transistors with Silicon MOS Technology

Yu-Chih Tseng† and Jeffrey Bokor

Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, California 94720

Ali Javey, Qian Wang, and Hongjie Dai

Department of Chemistry and Laboratory for Advanced Materials, Stanford University, Stanford, California 94305

We demonstrate a process that integrates carbon nanotube (CNT) transistors with silicon MOS technology, through the integration of around two thousand CNT devices with an MOS decoder circuit. Carbon nanotubes, grown using chemical vapor deposition at 1888 sites, form an integral part of the circuit. One or few nanotubes are grown at each site, and all 1888 sites can be individually addressed and characterized using the decoder circuit, using 22 binary inputs. Statistical analysis suggests that the diameter of the nanotubes plays an important role in determining the off-state leakage current of a CNT transistor. The integration scheme developed here allows the interconnection of CNT devices with MOS circuitry using an almost arbitrary choice of metal that provides good contact to both CNT and MOS devices. An integrated circuit technology combining both CNT and MOS devices may lead to novel circuit design, functionalities, and possibly improved performance.

Carbon-Nanotube Transistors: Intrinsic Performance and Fabrication

Fumiyuki Nihey, NEC Fundamental and Environmental Research Laboratories

Carbon nanotubes (CNTs), discovered in 1991 by Sumio Iijima at NEC Tsukuba Laboratory, have attracted much attention as possibly essential ingredients for future nanoelectronics because of their very narrow diameters of an order of 1 nm, the possible engineering of electronic properties determined by their diameter and chirality, and remarkably large current capacity.

We have investigated the intrinsic transconductance of CNTFETs with CNTs grown by chemical vapor deposition (CVD). The measured transconductance at a drain voltage of -1 V was 8.7 uS for a CNT with a diameter of 1.5 nm. Very high intrinsic transconductance of 20 uS was estimated by considering the contribution of parasitic resistance. Apparent and intrinsic transconductance per unit channel width were 5800 uS/um and 13000 uS/um, respectively. These are considerably larger than those for the state-of-the-art Si MOSFETs. We expect the performance of CNTFETs will advance further by improving CNT quality and by optimizing device structures.

We have also developed a novel method for iron nanoparticle synthesis that can easily control both their positions and diameters significantly smaller than the lithography limit, and have demonstrated diameter- and position-controlled CNT growth from the nanoparticles. We patterned iron particles having a 1.7 nm +/- 0.6 nm diameter distribution within a positioning accuracy of +/-5 nm by means of ``lithographically-anchored nanoparticle synthesis (LANS)`` method. CNTs were successfully grown by ethanol CVD. This method is readily applicable to the fabrication of high-performance CNTFETs.

THE MOLECULAR FOUNDRY PROGRAM

Jeffrey Bokor
Deputy Director for Science
The Molecular Foundry
Lawrence Berkeley National Laboratories
Berkeley, CA 94720
jbokor@lbl.gov

The Molecular Foundry is one of five DOE Nanoscale Science Research Centers. The Foundry is focused on the dissemination of techniques and methods for fabricating nanoscale patterned materials, to enable scientists from a wide range of disciplines to engage in this research. The Foundry will be a housed in a new laboratory building that is scheduled for completion in 2006. At that time it will contain facilities and staff to support users interested in nanolithography (e-beam lithography and stamping tool), organic nanostructures (polymers, dendrimers), inorganic nanostructures (vapor phase and colloidal growth of nanocrystals, nanotubes and nanowires), theory and simulation of nanostructures (empirical pseudopotential, density functional, Green's function techniques, Molecular Dynamics), imaging (STM and AFM based tools), and biological nanostructures (cell culture, biopolymer synthesis). During the construction phase, a limited foundry program is in operation.

The Foundry is charged to provide state-of-the-art instruments and expert, dedicated staff proficient in the newest, often unpublished, techniques that make use of those instruments. Investigators from academic, government, and industrial laboratories are invited to submit proposals for work at the Foundry. This poster will describe the Molecular Foundry program in more detail.

Phonon Engineering Approach for the Performance Enhancement of Nano-Devices

A. A. Balandin, E.P. Pokatilov and D.L. Nika
Nano-Device Laboratory, Department of Electrical Engineering, University of California
Riverside, California 92521 USA
E-mail: *alexb@ee.ucr.edu* *Web: http://ndl.ee.ucr.edu/*

Interaction of acoustic phonons with electrons plays an important role in the physics of semiconductors and their heterostructures. In many important semiconductors, acoustic phonons determine the heat transport, processes of the carrier relaxation and recombination, as well as limit the electron mobility at T>50K. In nanostructures with the feature size much smaller than the phonon mean free path Ë (note Ë~50nm-100nm in Si at T=300K), the quantization and dispersion modification of the spatially confined acoustic phonon strongly influences the electron – phonon scattering rates. In this presentation we propose a novel *phonon engineering* approach for the electron mobility enhancement in the "acoustically mismatched" nanostructures made of the "acoustically hard/fast" device channel and the "acoustically soft/slow" phonon damping barriers. The redistribution of the phonon modes results in the phonon depletion in the channel [1] and the corresponding enhancement of the electron mobility [2].

[1]. E.P. Pokatilov, D.L. Nika, A.A. Balandin, *Appl. Phys. Lett.*, **85**, 825 (2004).
[2]. A.A. Balandin, D.L. Nika, E.P. Pokatilov, *Appl. Phys. Lett*., to appear, 2005.

Nanotechnology Material Metrology Project

Toshio Mugishima
Nanotechnology and Materials Technology Development Department
New Energy and Industrial Technology Development Organization

Common metrological technology required for nanotechnology is being developed, and R&D to create ultra-fine substance structures is being accelerated by preparing new reference materials for nanomaterials to guarantee reliability, based on the national standard.

By FY2007, we will develop precise and accurate measuring technology for the thermophysical properties of thin films and boundary thermal resistances, and for the dynamic and structural characteristics of nanoparticles, the structural characteristics of nanopores, and the composition of nanosurfaces. More than eight new kinds of reference materials related to such properties will be developed.

In R&D relating to the thermohysical properties of thin films between 75 nm to 200 nm thick deposited on transparent substrates, the interface between the film and the substrate was heated for a very short time by a picosecond (one trillionth of a second) laser pulse and heat diffusion as fast as a few dozen to a few hundred picoseconds across the film thickness direction was observed for the first time. Based on this new measurement technique, reference thin films for thermal diffusivity measurements were developed, and by using it to calibrate measuring instruments in practical use, many researchers and engineers will be able to measure the thermohysical properties of thin films reliably based on a national standard.

Title:

The technology to synthesize nanoparticles and organize them to functional devices

Author Name: Akihiko Nishiki

Title: Project Coordinator

Affiation: New Energy and Industrial Technology Development Organization

NANOTECHNOLOGY AND MATERIALS TECHNOLOGY DEVELOPMENT DEPT.

Abstract:

New Energy and Industrial Technology Development Organization (NEDO) in Japan is promoting a Nanotechnology Program by the Ministry of Economy, Trade and Industry (METI). This Nanotechnology Program includes a project that the technology to synthesize nanoparticles and organize them to functional devices. Japan chemical Innovation Institute (JCII) under the commission of NEDO conducts this project. This project will run for 5 years form FY2001 to FY2005. We intend to establish the technology of synthesizing the single nanometer sized, uniform, stable particles. We also intend to establish the technology to fabricate and evaluate the functional devices and nanocomposite that have the ordered structure. We will report on current status concerning the following research and development themes;

1. Technology to synthesize single nanometer sized particles at high rate.
2. Technology to modify the surface of nanoparticles and form thin films.
3. Technology to fabricate functional devices.

THE NATIONAL NANOTECHNOLOGY INITIATIVE
Research and Development Funding in the President's 2006 Budget

President Bush's 2006 Budget provides over $1 billion for the multiagency National Nanotechnology Initiative (NNI), bringing the total NNI investment since its inception in FY 2001 to over $5 billion. This sustained investment will advance our understanding of the unique phenomena and processes that occur at the nanometer scale and expedite the responsible use of this knowledge to achieve advances in medicine, manufacturing, high-performance materials, information technology, and energy and environmental technologies.

The NNI supports the advancement of nanotechnology by funding cutting-edge research, creating multidisciplinary centers of excellence, and developing key research infrastructure. It also supports activities aimed at addressing the societal implications of nanotechnology, including ethical, legal, human and environmental health, and workforce related issues.

The largest investments continue to be made by National Science Foundation, reflecting that agency's broad mission in supporting fundamental research across all disciplines of science and engineering; Department of Energy, which is in the process of completing five Nanoscale Science Research Centers that will provide research equipment and infrastructure that will be broadly available to researchers from across the scientific research community; and Department of Defense, with its emphasis on development of materials, devices and systems that address the agency's mission. The FY 2006 request by Department of Human and Health Services (HHS) includes programs at National Institute of Health (NIH) emphasizing nanotechnology-based biomedical advances occurring at the intersection of biology and the physical sciences, such as the National Cancer Institute's Alliance for Nanotechnology in Cancer (http://nano.cancer.gov), and at the National Institute of Occupational Safety and Health (NIOSH) that address implications and applications of nanotechnology for health and safety in the workplace.

Nationtal Nanotechnology Initiative
(Budget authority, dollars in millions)

	2004 Actual	2005 Estimate	2006 Request
National Science Foundation	256	338	344
Defense	291	257	230
Energy	202	210	207
HHS (NIH)	106	142	144
Commerce (NIST)	77	75	75
NASA	47	45	32
Agriculture	2	3	11
Environmental Protection Agency	5	5	5
HHS (NIOSH)		3	3
Justice	2	2	2
Homeland Security	1	1	1
Total	989	1081	1054

With the addition of NIOSH, 11 federal agencies currently fund nanotechnology research and development under the NNI, and another 11 participate in coordination. Agencies that have joined the NNI as participants over the past year include the U.S. Patent and Trademark Office and the Consumer Product Safety Commission, indicating the increasing importance of commercialization activities.

The NNI Strategic Plan released in 2004 articulates the vision and goals for the program, and describes activities aimed at achieving those goals as well as the overall investment strategy. It also describes where agency missions, interests, and needs intersect with the NNI areas of investment and anticipated nanotechnology applications. Additional details are included in the NNI Strategic Plan and the NNI Supplement to the President's FY 2006 Budget, both of which are available at www.nano.gov.

Performance, Design, and Modeling of Bio-Assembled Carbon Nanotube FETs

Khairul Alam, Nicolas Bruque, Rajeev Pandey, and Roger Lake
Department of Electrical Engineering, University of California, Riverside, CA 92521

Optimal designs for bio-assembled carbon nanotube FETs (CNTFETs) are determined, and their performance metrics of inverse subthreshold slope, on-off current ratio, delay time and cutoff frequency are calculated and presented. These CNTFETs are shown to have excellent performance metrics with THz cutoff frequencies, 100fs delay times, and inverse subthreshold slopes between 60-70 mV/decade. Coulomb blockade provides suppression of the ambipolar leakage current.

Experimental work is underway to assemble CNTs using amide / DNA and glutamate / PNA (peptide nucleic acid) linkers. To support that effort calculations of the energy levels and orbitals have been performed for the CNT-Glutamate-PNA system and the CNT-amide-DNA. The results indicate that the Glutamate state lies in the gap of the CNT near the valence band which is good for hole transport and the LUMO of the DNA-amide-CNT system extends through the amide linker indicating good electron transfer. Transmission through a CNT-Peptide-CNT assembly has been simulated with our in-house ab initio DFT FIREBALL / NEGF code. The results indicate good electrical transport for p-type CNTs.

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Artificial bone synthesis based on hydroxyapatite binding protein template

Seung-Wuk Lee, Jie Song, and Carolyn R. Bertozzi

Molecular Foundry, Materials Sciences Division, Lawrence Berkeley National Laboratory, Departments of Chemistry and Molecular and Cell Biology, and Howard Hughes Medical Institute, University of California, Berkeley, California 94720

Hydroxyapatite nanocrystals were nucleated based on hydroxyapatite binding proteins templates. Hydroxyapatite binding peptides were selected using combinatorial phage library display. The phage library contained one billion different amino acid sequences which were expressed on pIII coat proteins of M13 bacteriophage, then screened to find specific binding moieties against single crystalline hydroxyapatite surfaces. After fourth round of selection, pseudo-repetitive consensus amino acid sequences possessing periodic hydroxyl side chains in every two or three amino acid sequences were obtained. These sequences resembled the (Gly-Pro-Hyp)$_x$ repeat of human type I collagen, a major component of extracellular matrices of natural bone. In addition, a consistent presence of basic amino acid residues was also observed. These peptides were synthesized and then used to template the nucleation and growth of hydroxyapatite nanocrystals. Various electron microscopy techniques (TEM, SEM and EDS) were used to characterize the shape and orientation of mineral growth of the peptide-mineral composites. These mineral binding peptides are expected to be further incorporated into 3-dimensional biomimetic bonelike materials.

The National Nanotechnology Infrastructure Network

Professor Yoshio Nishi and Professor Sandip Tiwari
Stanford University and Cornell University

The **National Nanotechnology Infrastructure Network** (NNIN) is an integrated networked partnership of user facilities, supported by the National Science Foundation, serving the needs of nanoscale science, engineering and technology.

The mission of NNIN is to enable rapid advancements in science, engineering and technology at the nano-scale by efficient access to nanotechnology infrastructure. We provide shared open, geographically diverse laboratories, each with specific areas of technical excellence, and provide fabrication, synthesis, characterization, and integration resources to build structures, devices, and systems from atomic to complex large-scales. Our users belong to diverse areas: astronomy, plant pathology, materials science, physics, chemistry, life-sciences, various branches of engineering, etc., and come from academe, national laboratories, and industry. Users can perform research on-site using our extensive facility equipment, training and staff support. For many tasks, remote usage is also feasible. External users typically spend a week or two, or commute, to complete their work although longer visits are possible. We help users succeed by providing strong pre-visit technical interaction, mechanisms that let users protect their intellectual property, and strong training and knowledge support. NNIN's success comes from an emphasis on supporting interdisciplinary and emerging areas with openness to the development and use of new materials, techniques, and applications. Examples of our unique approaches are: Domain Experts who provide technical expertise and support so that users can employ techniques and knowledge of other disciplines. Common examples are chemistry- or biology-based techniques, computation and modeling, nanoscale characterization, novel growth techniques, etc. Web-based educational and technical resources are also available for a variety of research areas, including a soon to appear Open Textbook on Nanotechnology. Graduate and undergraduate students find our mentoring web-based media useful for learning about how to make good presentations as well as making career decisions. Through equal access to all projects independent of origin; training, education and hands-on support in conduct of experimental tasks; and a commitment to social and ethical consciousness, outreach, and development of web-based infrastructure resources, we provide an open environment for success of the national nanotechnology enterprise.

Viral Based Assembly of Nanostructures and Nanoelectronics

Chunglin Tsai, Department of Electrical Engineering; Cengiz Ozkan, Department of Mechanical Engineering; University of California, Riverside 92521

ABSTRACT:
Viruses of various geometrical shapes have been exploited as higher hierarchical biomolecules in self-assembled nanoelectronics structures. We have demonstrated several organic virus particle and inorganic nanoparticle peptide-directed conjugations, including rod-shaped tobacco mosaic virus (TMV) with quantum dots (QDs) and icosahedral poliovirus (PV) with single-walled carbon nanotubes (SWCNTs) using ethylene carbodiimide (EDC) coupling chemistry. In order to exploit these nanostructures as interconnects in nanoelectronics, the attachment between platinum (Pt) particles and virions was also performed by reducing Pt ions onto the capsids of viruses to make them conductive. Characterizations such as scanning and tunneling electron microscopy, fluorescent imaging, and Fourier transform infrared spectroscopy were shown to prove the organic-inorganic conjugated heterostructures.

Nano-patterned Liquid Metal Electrode for the Synthesis of Novel Prussian Blue Nanotubes and Nanowires

Sathyajith Ravindran, Krishna V. Singh, Department of Chemical Engineering; Senthil Andavan GT, Department of Chemistry; Mihrimah Ozkan, Department of Electrical Engineering; Cengiz Ozkan, Department of Mechanical Engineering, Unviersity of California, Riverside 92521; Yan Gao, Evelyn Hu, Department of Electrical Engineering, University of California, Santa Barbara 93106

ABSTRACT:
We report for the first time the fabrication of prussian blue nanotubes via a novel technique wherein a liquid metal surface is nano patterned with a porous polycarbonate membrane used as a hard mask. Prussian blue as 1D nanowires and nanotube are excellent candidates for ultra low level sensing, optical wave guides and model systems to test the one-dimensional Ising model. One of the most feasible techniques for nanowire fabrication is to use porous template. However prussian blue dissolves in strong acids and decomposes in strong bases. Conventional procedures which use porous alumina with a back-side metal contact need strong acids and bases in the various steps of the nanowire fabrication. We report a novel technique which will pave way for the facile synthesis of nanowires and nanotubes of materials that are sensitive to strong acidic or basic environment. Hence, nano patterning of a liquid metal (Hg which functions as a top-side metal contact) with polycarbonate membrane instead of porous alumina membrane eliminates the use of both strong acid and base during the fabrication of nanowires. With this innovative technique we report the synthesis of novel organic prussian blue nanotubes and nanowires.

SWNT-PNA-SWNT Conjugates: Synthesis, Characterization and Modeling

Krishna V. Singh[1], Xu Wang[1], Rajeev R. Pandey [2′], Roger Lake[2], Cengiz S. Ozkan[3] and Mihri Ozkan[2*]
[1]Department of Chemical and Environmental Engineering
[2]Department of Electrical Engineering
[3]Department of Mechanical Engineering
University of California Riverside, Riverside, CA 92521
′University of California Los Angeles, Los Angeles, CA 90095

*corresponding author: mihri@ee.ucr.edu

ABSTRACT

Imparting molecular recognition to carbon nanotubes (CNTs) by conjugating them with bio-molecules has been an area of great interest as the resulting highly functionalized CNT-bioconjugates find their applications in various fields like molecular level electronics, pharmaceuticals, drug delivery, novel materials and many others. In this work we demonstrate the synthesis of functionally engineered single walled carbon nanotubes (SWNTs)-peptide nucleic acid (PNA) conjugates especially for nanoelectronic applications. Here, we exploited the exceptional structural and chemical advantages of PNA (an artificial analogue of DNA) to join SWNTs ropes. SWNT-PNA-SWNT conjugates were synthesized using carbodiimide coupling chemistry and characterized by host of techniques like scanning electron microscopy, atomic force microscopy and Fourier transform infrared spectroscopy. The results from different techniques confirm the formation of these conjugates. To further study these conjugates for electron transfer, models of SWNT-PNA interface were simulated using the PM3 semi-empirical package in Gaussian03 RevB.03 program suite. Simulations show that the highest occupied molecular orbital lies on the glutamate linker and indicate that this interface state will align closely to the valence band of the extended SWNT facilitating charge transfer. The unique electrical and structural properties of these conjugates make them a potential candidate for application in CNT based nanodevices.

Organic and Inorganic Nanoparticle Hybrids

Nathaniel G. Portney[1], Krishna Singh[1], Sumit Chaudhary[2], Giuseppe Destito[3], Anette Schneemann[3], Marianne Manchester[3, 4], Mihri Ozkan[2*]

[1]Department of Chemical and Environmental Engineering
[2]Department of Electrical Engineering
University of California, Riverside, California 92521
Departments of [3]Molecular Biology,
[4]Center for Integrative Molecular Biosciences,
The Scripps Research Institute, 10550 North Torrey Pines Road, La Jolla, California 92037
* The corresponding author: Email mihri@ee.ucr.edu. Phone: 951-827-2900. Fax: 951-827-2525

Viruses are exemplary models in nanoassembly for their regular geometries, well characterized surface properties, and nanoscale dimensions. Armed with versatile tools aimed at site directed mutagenesis to modify the virion's surface, conjugation chemistry for capsid coupling, and manipulation of nanoparticles, we have demonstrated nanoscale assembly of inorganic carbon nanotubes and quantum dots with engineered viruses to produce an intimate array of hybrid structures. These hybrid assemblies can be used as building blocks of future's nanoelectronic devices.

ZnO Quantum Dots for Spintronic and Optoelectronic Applications: Excitons, Phonons and Spin Relaxation

Vladimir A. Fonoberov and Alexander A. Balandin
Nano-Device Laboratory, Department of Electrical Engineering, University of California, Riverside, California 92521 USA
E-mail: alexb@ee.ucr.edu Web: http://ndl.ee.ucr.edu/

ZnO nanostructures, such as quantum dots (QDs), have recently attracted significant attention for spintronic and optoelectronic applications. However, many properties of ZnO nanostructures are not well understood yet. In this poster we present our recent theoretical and experimental results, which (i) clarify the origin of ultraviolet (UV) photoluminescence (PL) from ZnO QDs [1], (ii) explain the optical phonon peak shifts in measured Raman spectra [2], (iii) describe the dot radius dependence of the exciton lifetime in ZnO QDs [3], and (iv) provide estimates for the exciton "dead-layer" in ZnO nanostructures. We also discuss our approach for investigation of the spin-orbit interaction and spin relaxation in ZnO quantum dots embedded into a matrix material. We found that depending on the surface passivation technique, UV PL in ZnO QDs can be attributed to either confined excitons or surface-bound ionized acceptor-exciton complexes. The strength of phonon confinement in ZnO QDs has been studied both theoretically and experimentally.

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[2] K.A. Alim, V.A. Fonoberov and A.A. Balandin, Appl. Phys. Lett., 86, 053103 (2005).
[3] V.A. Fonoberov and A.A. Balandin, Phys. Rev. B 70, 195410 (2004).

The Nano/Bio Interface Center

Director: Dawn Bonnell
Assoc. Director: Yale Goldman
The University of Pennsylvania
Philadelphia, PA

Some of the most challenging issues in the ‘Nanotechnology Era’ are associated with interfacing physical and biological systems. The fundamental principles of molecular function at interfaces will dictate how it can be exploited both in an engineering sense and in understanding basic biological processes. The National Science Foundation supported ***Nano/Bio Interface Center*.** at the University of Pennsylvania exploits recognized strengths in design of molecular function and quantification of individual molecules. The study of the ethics of nano-bio technology is an integral part of the program. The Center unites investigators from ten departments in three schools (SEAS, SoM, and SAS) to provide, not only new directions for the life sciences, but also for engineering in a two-way flow essential to fully realizing the benefits of the intersection of biology with nanotechnology.

The research program is structured around two major scientific themes (Biomolecular Opto-Electronic Function and Molecular Motion) and two cross cutting initiatives (Single Molecule Probes and Ethics). The experimental facilities (The Molecular/Nanostructure Innovation Lab) will be a national resource for single molecule analysis.

This poster will highlight the current activities and recent scientific accomplishments.

Fabrication of Functional Architectures Through the Directed Assembly of Nanoscale Building Block

Leonard Spinu, Leszek Malkinski, Weilie Zhou, Scott Whittenburg, and John B. Wiley,
Advanced Materials Research Institute, University of New Orleans
Jin-Seung Jung
Department of Chemistry, Kangnung National University, Korea

This presentation summarizes the efforts of the University of New Orleans's multidisciplinary team in developing functional architectures by the directed assembly of nanoscale building blocks into nanolithographically-patterned arrays. This project is sponsored by NSF through Nanoscale Interdisciplinary Research Teams program.

The building block components, including simple wires, complex wires (core-shell, coaxial, superlattice, hollow, porous, and corrugated), spheres, rings, and disks, are made from porous templates with a combination of chemical and electrochemical methods. Electron-beam nanolithography allows the preparation of a series of patterns with well-defined features. The nanocomponents are assembled within the patterned arrays by physical and/or chemical means. The directed assembly of building blocks into these arrays will result in intricate 3-D architectures not accessible by traditional thin film technologies and lead to a new series of designs beyond those derived from the simple miniaturization of known constructs. Specific constructs that exploit nanostructured magnetic components will be sought for applications in high-frequency tunable filters, magnetotransport arrays, and simple mechanical systems. Properties are investigated as a function of building block materials, dimensions, and geometries as well as the geometries of the patterned arrays. Micromagnetics modeling of individual and collective properties, along with feedback from property measurements, allows for an active refinement of architectural designs.

Electrical Characterization of Bio-templated Nanowires

Yan Gao[1], Jing C. Zhou[2], Chung-Yi Chiang[3], Yu Huang[3], Ki Tae Nam[3], Angela Belcher[3], Bruce Dunn[3], Evelyn Hu[1]

[1]*Materials Department, UCSB,*
[2]*Materials Science and Engineering, UCLA*
[3]*Materials Science & Engineering and Biological Engineering, MIT*

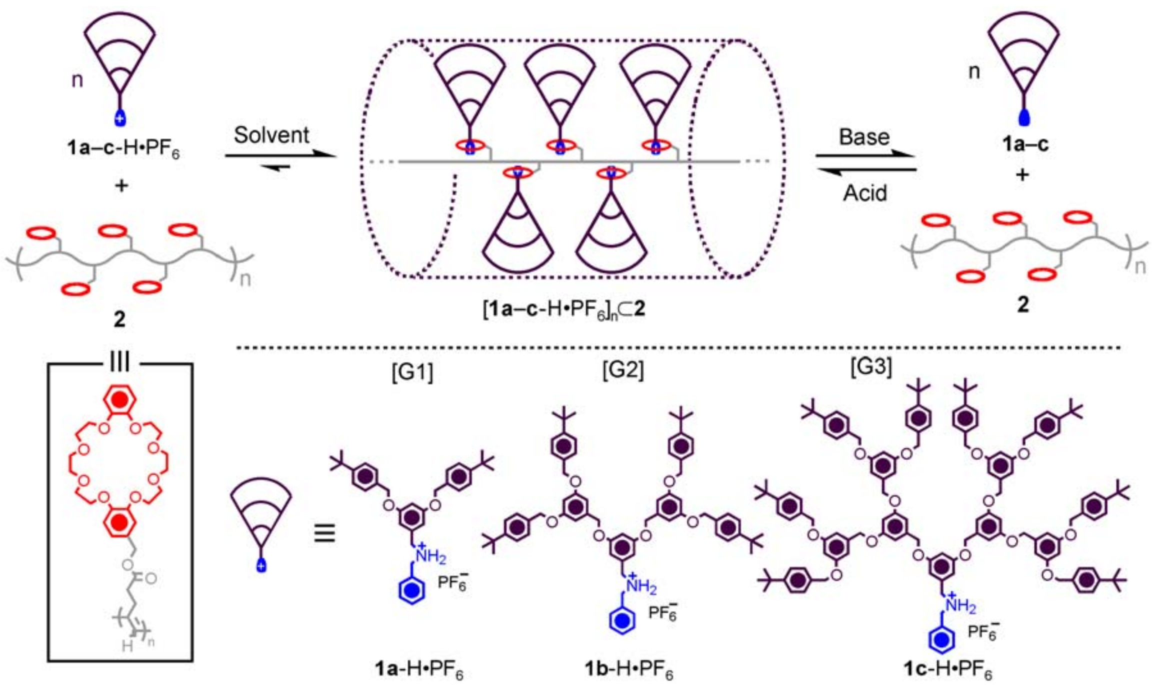
The semiconductor technology is reaching practical and theoretical limits for conventional top-down lithographic technique. A number of different techniques are being pursued for ‘bottom-up’ patterning of electronic device components, where accuracy of structure dimensions and precision of assembly are mediated by chemical or biological selectivity. Nanoscale electronic interconnects or nanowires are intrinsic building blocks of complex electronic nanosystems; utilizing natural templates for the wire formation, such as engineered microtubules or genetically engineered M13 coliphage can provide control of the wire dimensions, and ultimately over its electronic properties. It is critically important to characterize the conducting properties of these bio-templated nanowires, relating conductivity to structure, choice and method of templating, and ultimately assessing the nature of the contact resistance of nanowires to nanostructured device. This study describes preliminary work in the systematic electrical characterization of two kinds of bio-templated nanowires: Microtubule-templated Ni wires whose diameters range from 30-150nm, several microns in length; and Phage-templated metal (Au, Ag) wires, approximately 1 micron in length and 20nm in diameter.
Either Focused Ion Beam (FIB) metal deposition or electron-beam writing was applied to make contact on the wires. Our preliminary current-voltage curves have been made on these nanowires. Further experiments include characterizing the resistance as a function of temperature, and annealing conditions. Correlations between the conductivity and wire structure and dimensions will be carried out.

Polymer Nanostructures with Controllable Rigidity

Ken C.-F. Leung,[1] Paula Mendes,[1] Sergei Magonov,[2] Brian H. Northrop,[1] Amar H. Flood,[1] Sangcheol Kim,[3] Edward J. Kramer,[3] Hsian-Rong Tseng[1] and J. Fraser Stoddart*[1]

[1]*California NanoSystems Institute and the Department of Chemistry and Biochemistry, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90095-1569, USA*
[2]*Digital Instruments,Veeco Metrology Group, 112 Robin Hill Road, Santa Barbara, CA 93117, USA.* [3]*Department of Chemical Engineering, University of California, Santa Barbara, CA 93106-5080, USA.*

Acid-base switchable supramolecular dendronized polyacetylenes [**1a–c**-H•PF$_6$]$_n$⊂**2** from generation one [G1] to generation three [G3] (**Scheme**) were constructed using multiple self-assembly processes between dendritic dialkylammonium salts **1a–c**-H•PF$_6$ and a dibenzo[24]crown-8-containing polyacetylene **2**. The formations of the supramolecular systems are acid-base switchable to either an ON state (rigid dendronized polymers) or an OFF state (flexible polymers). Thus, by controlling the superstructures of the supramolecular polymers, it is possible to induce conformational changes within the backbone of **2** with the [G1]–[G3] dendrons **1a–c**-H•PF$_6$. The supramolecular dendronized polymers, as well as their threading-dethreading properties, were characterized by gel permeation chromatography, UV absorption and ^{1}H NMR spectroscopies, laser light scattering and atomic force microscopy. These results and their implications for device fabrication will be discussed.



Theoretical and experimental study of single electron tunneling in self-assembled molecules

W. Chen, E. Cimpoiasu, J.B. Li, X. Liu, J. Lukens, S. Roberts, N. Simonian, O. Turel,
A. Mayr, and K.K. Likharev
Stony Brook University, Stony Brook, NY 11794

We will present the first results of a coordinated theoretical and experimental study of electronic transport through specially synthesized molecules in which diimide acceptor groups are connected with oligo(phenyleneethynylene) chains, with isocyanide end groups [1]. Experimentally, we let the molecules self-assemble across few nm-gaps between thin-film gold electrodes, with highly doped silicon substrates used as backgate electrodes. The self-assembly yield is still very low, but we have got substantial experimental evidence of sequential single-electrode tunneling. The experimental data are being compared with results of theoretical calculations based on the general theory of single-electron tunneling in systems with discrete electron spectrum [2] in combination with DFT calculation of molecular spectra and orbitals, using the NRLMOL package [3].

The work was supported in part by AFOSR and NSF. Useful discussions with P. Allen, D. Averin, T. Baruah, M. Pederson and M. Reed are gratefully acknowledged.

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2. D. V. Averin, A. N. Korotkov, and K. K. Likharev, Phys. Rev. B, vol. 44, pp. 6199-6211, Sep. 1991
3. See http://cst-www.nrl.navy.mil/~nrlmol/.

Metal-coated carbon nanotube tips for Scanning Probe Microscopy

Erhan Yenilmez, Zhifeng Deng, Prof. Hongjie Dai, Prof. Kathryn A. Moler

Abstract:
High resolution scanning probe microscopy (SPM) is essential to characterize new materials and devices at nanometer scale. Carbon nanotubes can be used as ultra sharp tips for SPM. We have developed a process where we can grow single walled carbon nanotubes on a wafer of crystal silicon tips. Here we introduce new capabilities for carbon nanotube tips by coating them with metals. We make magnetic tips by coating cobalt for ultra high resolution magnetic force microscopy. We coat micrometers long carbon nanotube tips with metal and manipulate their orientation using focused ion beam. The metal coating makes these otherwise unsuitably floppy tips useful for high-aspect ratio imaging.
We demonstrate this capability on tall structures on micro-machined surfaces and biological samples. Metal-coated carbon nanotube tips are potentially useful for other force microscopy techniques as well.

Nano-scale patterning using diblock copolymer

Wen Feng, Zuoming Zhao, Tae-Sik Yoon, and Ya-Hong Xie
Department of Materials Science and Engineering, UCLA

Diblock copolymer films of polystyrene-b-polyisoprene (PS-PI) are investigated on Si substrates for bottom-up nano-scale patterning. The morphology evolution with polymer thickness is observed by using optical microscopy. As-coated polymer presents a very smooth surface. After annealing polymer over glass-transition temperature, the polymer exhibits a smooth surface only at certain thickness L_0. Using transmission electron microscopy, the microphase separation in polymer at different stages is studied. Clear phase separation is observed in the polymer after staining with osmium tetraoxide (OsO_4). As-spun PS-PI films already show observable phase separation. Long time annealing increases the range of ordering. Appearance of white holes indicates that the polymer with double-bond is removed from copolymer film after treatment with ozone. Scanning electron microscopy shows that polymer films after reactive ion etching give an ordered hole-pattern with 15nm in diameter and 30nm spacing, which can serve as the mask for nanometer scale patterning. The nano-scale patterning is also successfully demonstrated on silicon nitride. This method can be applied to a variety of substrates to provide templates for ordered nano-particle array which is required for the electronic, magnetic and optoelectronic applications.

Center for Nanoscale Systems

Jurriaan Gerretsen
Center for Nanoscale Systems, Cornell University

The Center for Nanoscale Systems (CNS) has assembled interdisciplinary teams to execute an aggressive and wide-ranging nanoscale science and engineering (NSE) research program. The CNS research mission is to substantially advance the impact of nanotechnology in future, high-performance, information technology systems. CNS teams are working in three focused research thrusts – nanoelectronics, nanophotonics, and nanomagnetics – with the collective purpose of understanding and controlling the electronic properties of materials at the nanoscale and of exploiting these material systems and associated nanoscale phenomena in technologically significant applications. The Center's primary research objective is to develop effective nanoscale devices and systems that have the potential of being revolutionary solutions for the demanding requirements of future computational, sensing, information storage and communication systems. CNS also seeks to develop and advance effective NSE research tools and techniques to support and further advance these information technology efforts. An overview will be given of the current research program, illustrated by highlights of the results obtained in the area of energy-efficient, programmable, double-gated transistors, high-speed spin-transfer-based MRAM compatible with CMOS technology, and high-speed, all-optical switching in silicon. Results of the highly successful CNS educational-outreach program will also be presented.

Spin Wave Bus – a New Approach to Nanoscale Devices Interconnection

Alexander Khitun and Kang L. Wang

Device Research Laboratory, Electrical Engineering Department,

MARCO Focus Center on Functional Engineered Nano Architectonics (FENA),

University of California at Los Angeles, Los Angeles, California, 90095-1594

Abstract

We propose and analyze a new kind of computational architectures using spin waves for signal transmission between nanometer scale devices. Information is encoded into the phase of spin waves propagating in a ferromagnetic film - Spin Wave Bus. The performance of the proposed architectures is illustrated by numerical modeling based on the experimental data for spin wave excitation and propagation in NiFe film. Potentially, the architectures with Spin Wave Bus may be beneficial in terms of power consumption and resolve the interconnect problem. Another expected benefit is in the enhanced logic functionality. Using phase logic, it is possible to realize a number of logic functions in one device. These advantages make the architectures with Spin Wave Bus very promising for application in ultra-high-density integrated circuits (more than 10^{10} devices per square inch). Potential issues will also be discussed.

Center for Scalable and Integrated Nanomanufacturing (SINAM)

National Science Foundation Nanoscale Science and Engineering Center (NSEC)
Award# DMI-0327077
Director: Xiang Zhang
5130 Etcheverry Hall, University of California, Berkeley, CA 94720-1740
Email: xzhang@me.berkeley.edu, Website: http://www.sinam.org

The Center for Scalable and Integrated NAno Manufacturing (SINAM) was established with major support from the National Science Foundation (NSF) on October 1st, 2003, as one of the Nano-scale Science and Engineering Centers (NSEC). SINAM has organized an exceptional team of scientists and engineers with diverse expertise from six institutions: University of California Los Angeles (UCLA), University of California Berkeley (UCB), Stanford University, University of California San Diego (UCSD), University of North Carolina Charlotte (UNCC), and HP Labs. This unique team possesses a broad spectrum of expertise in manufacturing, process design and modeling, material synthesis and characterization, physical science, and application development. SINAM is targeting the establishment of a new nano-manufacturing paradigm based on fundamental scientific research. This paradigm will forge a new education platform for multidisciplinary science and engineering by integrating research and education, and will enable an industrial quantum-leap by working closely with industry.

Ge quantum dot array selectively grown on Si patterned by diblock copolymer

Zuoming Zhao, Tae-Sik Yoon, Wen Feng, and Ya-Hong Xie
Department of Materials Science and Engineering, UCLA
Hyung-jun Kim and Kang L. Wang
Deapartment of Electrical Engineering, UCLA
Du Yeol Ryu and Thomas P. Russell
Polymer Science and Engineering Dep.,Univ. of Massachusetts, Amherst

Ge quantum dot arrays are selectively grown on Si (001) substrates with nano-scale patterns via solid-source molecular beam epitaxy. The density and dimension of the Ge quantum dots are strongly dependent on the nano-scale patterns created by poly(styrene-b-methyl methacrylate)(PS-PMMA) diblock copolymer. Thin film of PS-PMMA was annealed at 170^{o}C on neutral condition which is interfacially balanced. It allows the micro-domains to orient normal to the surface. After selective removal of PMMA, hexagonally ordered cylinder micro-domains offers a mask for pattern transfer to Si and SiO_2. Reactive ion etching transfers this pattern to substrates, which serves as a mask for Ge quantum dot growth. Ge quantum dots selectively nucleate and grow into the hole on both Si and Si with SiO_2 mask. The images from scanning electron microscopy show that Ge quantum dots with density of 8×10^{10} cm^{-2} and diameter of 30nm are achieved by selective growth on SiO_2 patterned substrates. This self-assembly and the growth thereafter demonstrate the possibility of patterning of nanostructures for integration of different materials on Si and offer new potentials for electronic and optoelectronic applications based on regular or homogeneous structures.

Title: Nanotechnology and Silicon Photonics

Contributor: Gernot S. Pomrenke

Abstract:

Beneath the pending challenges of electronic miniaturization, there exists a potential for a quiet revolution – extending the reach of silicon technology through nanotechnology into optical signal generation, processing, computing and storage. Enabling silicon technology with optical functionalities could advance numerous component and system capabilities by permitting monolithic integration of sensing, spectroscopy, signal processing and computing all on a single silicon chip. The technology offers lower power, higher bandwidth, and higher speed. Silicon optics could also be developed into a standalone technology, all-optic Si-based integrated microphotonics or nanophotonics, and do so rapidly and economically by leveraging the vast and advanced silicon infrastructure already in existence.

Silicon as an optical material also presents several challenges. These issues are fundamental limitations that arise from material properties, and result in difficulty of externally controlling silicon structures for optical modulation and switching, and in poor light emission from silicon devices due to silicon's indirect band gap, low EO and low non-linear coefficient. There is a need to develop novel devices that can overcome the limitations of Si-based photonics using novel materials and novel geometries, for enhancing the interaction of light with matter. Nanofabrication and nanostructures are seen as a potential solution to these challenges and limitations. Potential approaches will be discussed that range from Group IV based quantum wells, superlattices, quantum dots, nanoparticles to photonic bandgap structures, plasmon enabled components, novel doping and processing

Microstructure of Ge Self-Assembled Quantum Dots on Nanometer-Scale Patterned Si Substrate with Diblock Copolymer

Tae-Sik Yoon, Zuoming Zhao, Wen Feng, Biyun Li, Jeewhan Kim and Ya-Hong Xie

Department of Materials Science and Engineering, University of California at Los Angeles

Du Yeol Ryu and Thomas P. Russell

Department of Polymer Science and Engineering, University of Massachusetts, Amherst

Hyun-Mi Kim and Ki-Bum Kim
School of Materials Science and Engineering, Seoul National University, Korea

We investigate the microstructure of Ge self-assembled quantum dots (SAQDs) grown on Si (100) substrate patterned with hexagonally ordered, 25 nm deep holes of ~40 nm diameter using poly(styrene-b-methyl methacrylate)(PS-*b*-PMMA) diblock copolymer. Ge coverage of 9 Å thickness results in Ge dots nucleated exclusively inside the holes, starting at the edges of the holes. Moiré fringe analysis in transmission electron microscopy images reveals partial strain relaxation of about 72 % on average. The extent of strain relaxation is not uniform even within a single dot. The strain was found to be relaxed both elastically via the non-planar morphology and plastically through dislocation. This presentation reports the in-depth study of the microstructure of Ge dots grown on nano-scale patterned Si substrates. It also demonstrates for the first time a practical approach of fabricating Ge quantum dots on Si (001) with high density ~10^{10} cm^{-2} and high aspect ratio (height/diameter) of ~1 as required by device applications.

Title: Quantum Dots for Nanoscale Patterning of Self Assembled Monolayers

Authors: Chander Radhakrishnan†, Michael K.F.Lo†, Miguel A. Garcia-Garibay‡ and Harold G. Monbouquette†

† Department of Chemical Engineering, University of California Los Angeles
‡ Department of Chemistry and Biochemistry, University of California Los Angeles

Abstract

Semiconductor nanoparticles or quantum dots (Qdots) as they are known, have triggered a lot of research interest in the recent past due to their size tunable properties arising from quantum confinement effects. The versatility of Qdots is readily observed from their widespread applications in quantum devices, solar energy conversion, photocatalysis, biological imaging, etc.. We have researched the photocatalytic efficiency of II-VI Qdots (CdS, CdSe) for highly selective solution-phase reductions of aryl azides to aryl amines. The heterogeneous version of the same Qdot-photocatalyzed reaction has been studied using self-assembled monolayers of aryl azide-terminated thiolates on gold films. This surface reaction has been well characterized using an array of spectroscopic techniques (UV-vis, FTIR and XPS). By selective adsorption of Qdots in a predefined pattern on the monolayer surface, macro-scale (1 mm) patterns of aryl amine on an aryl azide monolayer have been generated. As the feature size of the pattern theoretically can be reduced to the size of a single Qdot (2-3 nm), this technique of photocatalytic patterning can potentially yield nanopatterns. Current research in our lab is focused on making micro-scale patterns (using micro-contact printing technique) and nano-scale patterns (using Langmuir-Blodgett Qdot assembly). The results of our efforts to create Qdot-photocatalyzed patterns from the macro to the nano-scale are presented.

Bionanotechnology in Tokyo Tech.

Susumu Kajiwara, Ph.D. Graduate School of Bioscience and Biotechnology, Tokyo Institute of Technology (Tokyo Tech.), JAPAN

The Graduate School of Bioscience and Biotechnology in Tokyo Tech. (established in 1992) have contributed to develop researches in the integrated field of life science and technology for 12 years. Especially, a new realms of life science and nanotechnology, bionanotechnology, is expected to produce major advances in molecular diagnostics, therapeutics, development of bio-materials and bioengineering, and then many researchers in our graduate school have gotten down to studying bionanotechnology R&D. At present, several research projects like as 1) development of probe microscope technology for visualization and manipulation of a bio-molecule such as protein and DNA, 2) development of high-precision peptide chips for detection and characterization of proteins and 3) development of nanotechnological methods regulating cell-cell and cell-matrix interactions for biomaterials, artificial organs, and delivery systems are performed aggressively. The poster in this conference demonstrates the contents of these projects.

Nano Patterned Epitaxial Graphite (NPEG): a new paradigm for nanoelectronics

The NSF (NIRT)/Intel funded NPEG project at the Georgia Institute of Technology explores the properties of patterned ultrathin graphite layers. The ultrathin graphite layers (from 1 to several tens of layers) are epitaxially grown on single crystal silicon carbide crystals. The layers are then patterned using a variety of standard lithography methods (e-beam, scanning probe and optical) to produce structures of which the electronic properties are determined. The electronic properties of the nanopatterned structures are predicted to be closely related to those of carbon nanotubes, which includes ballistic transport with mean free paths exceeding 1 µm at room temperature. The current status of the project is presented, which includes evidence of quantum coherence effects, a rudimentary room temperature transistor-like device, and results from various magneto-transport measurements showing room temperature mobilities exceeding 6000 cm2/Vs.

An Innovative Economic Development Strategy Based on the Collaborative Integration of Nanoscience and Microtechnologies

Robert D. "Skip" Rung
Oregon Nanoscience and Microtechnologies Institute (ONAMI)
www.onami.us

The state of Oregon is home to what is arguably the nation's most powerful collection of industrial micro- and nanotechnology R&D and leading-edge manufacturing assets, but has not been among the recognized leaders in research institution funding or reputation. Recognizing both the importance of early stage research for future job creation and the limitations of state funding for higher education, state government, industry and academic leaders have begun to establish 'signature research centers' at the intersection of three key elements: 1) excellent scientific research, 2) large future market opportunities, and 3) existing industry competencies. The first center, ONAMI, is a 'deep' collaboration combining the research assets of Oregon State University, Pacific Northwest National Laboratory, Portland State University, and the University of Oregon for the purpose of accelerating research growth and commercializing creative new technologies. This presentation will describe the structure and funding of ONAMI, its three carefully selected thrust areas, and give examples of promising innovations that have occurred at disciplinary and organizational boundaries. These include, inter alia, microchannel reactors for nanomaterial fabrication, bioreactors for nano-structured semiconductors, radically improved hemodialysis equipment, and highly efficient synthesis techniques for functionalized metal nanoparticles and dendrimers.

NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing

Ahmed Busnaina[1], Joey Mead[2], Glen Miller[3] and Carol Barry[2]
The NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing
[1]Northeastern University, Boston, MA 02115
[2]University of Massachusetts Lowell, Lowell, MA
[3]University of New Hampshire, Durham, NH

Abstract

The transfer of nano-science accomplishments into technology is severely hindered by a lack of understanding of barriers to nanoscale manufacturing. Commercial products cannot be realized without first answering many questions such as how one can assemble and wire billions of nano-scale devices together, or how one can prevent failures and avoid defects. The Center for high-rate nanomanufacturing is developing tools and processes that will enable high-rate/high-volume bottom-up, precise, parallel assembly of nanoelements (such as carbon nanotubes, nanoparticles, etc.) and polymer nanostructures. Proposed nanoelectronic devices using technologies beyond currently-deployed are many; mechanical or molecular switches, spin logic, phase logic, molecular devices, etc. Manufacturing of these switches and devices involves very diverse fabrication and assembly techniques that may involve top-down, bottom or both. There is a need to develop heterogeneous process integration such as combination of hierarchical directed assembly techniques with other processing techniques. High-throughput directed assembly and nanoscale components and interconnect reliability will also be essential in going beyond silicon. Another important nanomanufacturing issue is nanoscale defect mitigation and removal and defect tolerant materials, structures and processes in addition to nanoscale metrology tools, such as in-line or in-situ monitoring and feedback. Fundamental understanding and novel technology in high rate, high volume integration and assembly of robust tools and processes are addressed. Nanotemplates and tools are used to accelerate the creation of highly anticipated commercial products and will enable the creation of an entirely new generation of applications. This requires understanding what is essential for a rapid multi-step, high volume/high rate processes, as well as for accelerated-life testing of nanoelements and defect-tolerance.

Title: **Nanofabrication of Photonics Devices**

Authors: **L. Scaccabarozzi, Z. Rao, K. Yamanaka, J. S. Harris**

Abstract:
We present the fabrication techniques of three nanophotonic devices developed in the Solid State and Photonics laboratory at Stanford University. The first project consists in the realization of ultra-compact devices for non-linear optical frequency conversion. Their applications include integrated photonic circuits and all-optical networks. We have fabricated and characterized high-Q 1D-photonic crystal cavities embedded in AlGaAs/Al_xO_y waveguides and submicron birefringently phasematched waveguides.

The goal of the second project is to stop and coherently store light pulses with an all-optical adiabatic and reversible process. This process can be realized by using a series of ultra-high-Q 2D photonic crystal resonators, coupled to each other with a photonic crystal waveguide. The fabrication process, involving e-beam lithography and etching of high-aspect ratio structures, is presented.

The third topic is Very Small Apertured Lasers (VSAL). VSALs are very promising for realizing a compact, ultra-high density, near-field optical storage system. We present the fabrication and characterization of VSAL with a unique C-shaped nano-aperture on 1.5um edge emitting laser. A resonant transmission of the C-aperture is observed, which shows transmission efficiency of over 20 times higher than that of a same-area square aperture.

Creation of Polydiacetylene Molecular Wires through Controlled Chain Polymerization

Daisuke Takajo [a,b], Yuji Okawa [a,b] and Masakazu Aono [a,b,c]
[a] Nanomaterials Laboratories, National Institute for Materials Science (NIMS), Japan
[b] ICORP, Japan Science and Technology Agency (JST), Japan
[c] Department of Material and Life Science, Osaka University, Japan

Abstract:
In order to fabricate and interconnect molecular nanoelectronic circuits, a method that can create conjugated polymer nanowires at designated positions is desired. Here, we show that the initiation and termination of chain polymerization of molecules can be controlled by a tip of scanning tunneling microscope (STM), so that a conjugated polymer nanowire can be created at designated positions in the layer with a spatial precision of the order of 1 nm [1,2]. We used self-ordered layers of amphiphilic diacetylene compounds (10,12-pentacosadiynoic acid or 10,12-nonacosadiynoic acid) adsorbed on a graphite substrate. A chain polymerization was initiated by applying a pulsed voltage between the tip and the substrate. The obtained polydiacetylene nanowire, which can be clearly imaged by STM, is a linear conductive wire without any defects. The termination of the chain polymerization was also controlled by making an artificial structural defect in advance at a position along the path of propagation of chain polymerization using the STM tip. Recently, we have also succeeded in connecting polydiacetylene nanowires to gold nanoparticles.

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Status and the Next Step of Nanotechnology Research and Development in National Institute for Materials Science

Naoki Kishimoto
Integrated Strategy Office, National Institute for Materials Science (NIMS), Japan

Abstract:
The National Institute for Materials Science (NIMS) was founded in 2001 integrating two materials institutes: National Research Institute for Metals (NRIM) and National Institute for Research in Inorganic Materials (NIRIM). Coinciding with the integration period, the 2nd Science and Technology Basic Plan was issued and the NIMS has focused its programs onto Nanotechnology and Materials, among 4 focused R&D areas, including Life Science, Information Technology and Environment. The NIMS set the mid-term programs consisting of four categories Nanomaterials (NM), Safe Materials (SM), Environment and Energy Materials (EE) and Improvement of Intellectual Infrastructures (II). The highest priority has been cast on Nanomaterials. The investment percentages of the total budget ($170 M for 2005) are 28% for NM, 15% for SM, 12% for EE and 35% for II. The main topics range from atom manipulation, nanofabrication, nanotubes, biomaterials to nano-simulation, as well as nanoanalyses by STM, HVTEM, APM and SR. The emphasis on nanotechnology is still unchanged for the next-step. According to the 3rd Science and Technology Basic Plan (from F.Y. 2006), the NIMS is about to set the next mid-term programs (F.Y.2006 - 2010), whose main features are further concentration onto nanotechnology R&D and more emphasis on interdisciplinary areas, such as nano-bio materials.

Complementing CMOS with Semiconductor Nanowires

Gonzalo Fuentes-Iriarte[1], Geoffroy Hautier[1,2], Jan D'Haen[3], Thomas Hantschel[1], Geoffrey Pourtois[1], Bart Soree[1], Anne Verhulst[1], Wilfried Vandervorst[1], Marleen Van Hove Wim Magnus[1], Philippe Vereecken[1], S.H.Brongersma[1], and K. Maex[1,2]

[1]IMEC, Kapeldreef 75 B-3001, Leuven,
[2]EE. Department, K. U. Leuven, Belgium
[3]IMOMEC, Wetenschapspark 1, B-3590 Diepenbeek, Belgium
karen.maex@imec.be

Semiconducting nanowires are envisioned to be the ideal structures for introducing novel functionality in BEOL processing on top of the existing complexity of CMOS. They are grown using the vapor-liquid-solid approach and have shown great promise both in growth control and physical properties throughout the literature. The work for both III-V and group IV wires has shown that the field has matured sufficiently to justify an evaluation on full wafer level integration. In fact, the dimensions of the wires (20-100 nm) matches perfectly with the present size of contact and via holes obtained with state of the art optical lithography. Clearly this introduces new requirements in terms of thermal budget, catalyst size and placement control, and material compatibility with a cleanroom environment.

The objective of our program is firstly to identify catalysts and wire compositions that fall within the constraints imposed by the required further processing. Simultaneously realistic process flows for two or three terminal devices are being defined and tested. Also, new metrology requirements needed to characterize the structural and electrical properties are being developed.
This enables us to realistically evaluate the potential of adding novel functionality to the back-end-of-line with sufficient control and reproducibility.

IMEC Nanotechnology Programme : Integration of Carbon Nanotubes in silicon Technologies

K. Maex, C. Whelan, S. Esconjauregui Cruz, A. Roma Negreira, S. Brongersma, P.M. Vereecken, W. Vandervorst, W. Magnus
IMEC, Kapeldreef 75, 3001 Leuven, Belgium
karen.maex@imec.be

Carbon nanotubes (CNTs) can be thought of as tiny sheets of graphite rolled into seamless hollow cylinders. Multi-walled (MW) CNT’s are metallic and comprise several hollow cylinders fitted into each other. Single-walled (SW) CNTs consist of only one cylinder with an extremely small diameter (1.2-1.4 nm) and can be metallic or semiconducting depending on the chirality. CNT’s show promise for many electronic applications such as interconnects, memories, sensors, displays and transistors. Carbon based FET’s have been demonstrated for single CNT devices. However, to be economically viable, techniques have to be developed for large-scale batch-type manufacturing of CNT structures.

IMEC’s nanotechnology program is looking into possible ways of integrating CNTs into silicon technology for nanoelectronics. Currently, IMEC's work on CNTs focuses on obtaining an in-depth understanding of CNT synthesis through the study of catalyst-mediated chemical-vapor-deposition of CNTs on different substrates and catalysts. Based on this knowledge the growth and assembly of CNTs at predefined locations on patterned substrates with the correct conductivity type can be evaluated and an assessment of integration with existing Si technology can be made.

Exposure, Health and Environmental Risk Assessment of Nanoparticles

Takahiro Kobayashi,
Environmental Health Sciences Division, National Institute for Environmental Studies,
Tsukuba, 305-8506, Japan

Nanotechnology has huge potential to bring beneficial impact on society. Nanomaterials including nanoparticles play a key role in the nanotechnology. Due to the extremely small size, nanoparticles have new properties, such as different correspondence to external stimuli such as light, heat and voltage, electrical conductivity, strength, colour. Therefore, nanoparticles will be applied variety of industrial fields such as chemistry, electronics, cosmetics, medicine, food, environmental technology. Amount of production of nanoparticles will increase. Little has been done concerning the exposure assessment of nanoparticles in workplace, and health and environmental risk assessment. It is necessary to assess these risks. Therefore, our institute plans to investigate 1) number and weight of nanoparticles in the actual workplaces, 2) toxicokinetic behavior of nanoparticles, and 3) toxicological effects of nanoparticles using comprehensive, sensitive and specific biomarkers. Since lack of information about nanoparticles exposures, we need to investigate them at various selected workplaces having life cycle analysis of nanoparticles under consideration. Concerning 2) and 3), we have clarified that nanoparticles of carbon black has strong oxidative ability, induce strong inflammatory response, and aggravate asthma and pneumonia like symptoms. Our institute also plans to assess health risks of environmental nanoparticles such as nanoparticles derived from diesel exhaust.

Growing Germanium Nanowires on Silicon Substrates

Name: Hemanth Jagannathan
Department: Electrical Engineering
Advisor: Prof. Yoshio Nishi
Affiliation: Stanford University
Contact Information: Center for Integrated Systems, Room 304X
Stanford University, CA 94305
jhemanth@stanford.edu

Abstract-
With the rapid scaling of semiconductor devices for high performance and density, there is an ever-growing interest in investigating novel device structures and technologies. Nanowire technology builds on reasonable material know-how obtained from conventional bulk/SOI processing and has the benefit of being a truly scalable bottom up technology that would enable 3-D integration. This poster will introduce our capabilities of growing germanium nanowires on silicon substrates by the vapor-liquid-solid (VLS) mechanism and will discuss the initial studies conducted to control the position and orientation of nanowires. Nanowire growth was observed in temperatures ranging from 280°C to 320°C. Well controlled growth of nearly vertical epitaxial germanium nanowires was obtained at 315°C. To address the quality of the nanowires, we will also present detailed microstructure analysis performed on these epitaxial nanowires to show the absence of any visible defects or dislocations.

Nanophotonics for Biomedical Applications: Integrated Photonic Crystal Sensor

Ofer Levi, Wonjoo Suh, Meredith M. Lee, Shanhui Fan, and James S. Harris Jr.
Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
Phone: 1-650-723-0464, Fax: 1-650-723-4659
Contact E-MAIL: levi@snow.stanford.edu

Scaling and integrating optical devices for biological applications enables new functionality in the areas of bio-defense and clinical medicine. The small required sample volume and increased parallelism of such systems will allow for high throughput analysis. We have previously demonstrated a miniature integrated semiconductor fluorescence bio-sensor consisting of a VCSEL, PIN detector and filter for micro-total-analysis (μTAs) applications [1], and integrated the device with microfluidic channels for sensitive bio-sensing [2]. In this poster we present the design, simulation, and fabrication of a photonic crystal-based nanosensor that detects index of refraction changes in an aqueous solution. Light from a VCSEL is incident on a SiO2 substrate covered with a SiNx photonic crystal (PC) slab layer, and is reflected back to a detector. Some of the incident light is coupled into guided PC resonance modes; interference between this guided light and the original signal introduces resonance peaks in the reflection spectra [3]. If an aqueous solution flows through a nearby microfluidic channel and an analyte attaches to the sensor's surface, the detector will see a shift in the resonance peaks. Our poster highlights recent technical achievements including nanofabrication (E-beam, optical lithography) and characterization (SEM, Focused Ion Beam) results.

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Controlled Formation of Silicon Nanowire Arrays

Y.-L. Chang, S. S. Yi, E. Chow, G. Girolami, J. Albuschies, J. Amano
Agilent Technologies, Agilent Laboratories
3500 Deer Creek Road, MS 26M, Palo Alto, CA 94304
ying-lan_chang@agilent.com

Semiconductor nanowires represent an important class of nanostructured materials with the potential to impact applications from nanoscale electronics to biotechnology. As an example, field effect transistors based on silicon nanowires (SiNWs) and carbon nanotubes, have been demonstrated as good candidates for ultrasensitive, miniaturized molecule sensors[1,2]. Because of the high surface-to-volume ratio of the nanostructures, their electronic characteristics may be sensitive enough to a very small amount of charge transfer such that single molecule detection becomes possible[1].

Most of the existing fabrication methods for nanowire devices rely on assembly of nanometer-scale colloidal catalyst particles. It is important, yet challenging, to control the placement of these particles with the precision required to form large-scale arrays. As a result, post-growth flow-directed and electric-field assisted assembly techniques have been proposed and demonstrated[3,4]. However, such approaches may not be suitable for nanowires with small diameters.

In this report, a pathway to fabricating large scale, high-density nanowire arrays using standard semiconductor processes is described. The fabrication process begins with a doped Si wafer with 160 nm thermal oxide. Electron-beam lithography is utilized to define the location of catalyst. The metal catalyst, *e.g.* Au nanocluster, used for mediating growth of silicon nanowire is created by electron-beam evaporation, followed by metal lift-off. The sizes of metal catalyst controlling the diameters of SiNWs can be tailored by the electron-beam lithography and metal deposition steps. The nanowire growth process is performed at 550^{o}C using disilane as a precursor and hydrogen as carrier gas. SiNWs with diameters as small as 20 nm have been obtained. The length of SiNWs in the range of 1-5 micrometer can be tailored by controlling growth time. Transmission electron microscopy measurement indicates the single crystalline quality of nanowires. The as grown SiNWs on thermal oxide are randomly oriented. An ion-irradiation process is utilized to align the SiNWs in a desired manner[5]. Arrays of high density SiNWs have been successfully demonstrated. Finally, electron-beam lithography and electron-beam evaporation are utilized to form metal electrodes with desired spacing, thereby resulting in arrays of SiNW devices with desired location and density.

The method described herein, utilizing standard semiconductor fabrication processes, may serve as the basis for forming high density nanoscale sensors that can be integrated with microfluidics and CMOS driver circuits.

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Nanotechnology at NIST
Debra Kaiser

No abstract received

Network for Computational Nanotechnology

Prof. Mark Lundstrom
Purdue University

No abstract received