

2007 Micro/Nano 25 Winners

Engineered Carbon Nanotube (CNT) and Nanofiber Buckypapers—Florida State Univ. www.fsu.edu

These materials are macroscopic or continuous thin films or membranes comprised of randomly oriented and magnetically aligned CNTs and nanofibers. These buckypapers combine the advantages of large dimensions, superior electrical conductivity, nanotube alignment, and continuous production.

Enhanced Deformable Mirror (DM)—Boston Micromachines Corp. www.bostonmicromachines.com

These devices are used for ultra-high resolution retinal imaging, which is necessary for the early detection of ocular diseases. An enhancement of the Multi-DM, this new mirror delivers increased stroke while maintaining high resolution. The mirror's 3 kHz frequency capability allows for high-speed real-time imaging with a 6-mm aperture perfectly suited for a dilated pupil.

Functionalized Nanoporous Thin Film (FNTF)—Pacific Northwest National Laboratory www.pnl.gov

FNTF is a customized coating that preconcentrates heavy metals in water, creating samples that increase the detection sensitivity of x-ray fluorescence (XRF) spectroscopy by up to 1,000x. FNTF-coated XRF sampling disks can preconcentrate selected heavy metals from liquid samples, which then presents a solid sample to the XRF instrument.

GLAD, Glancing Angle Deposition—Micralyne, Inc. www.micralyne.com

GLAD is a proprietary physical vapor deposition (PVD) technology used to fabricate porous thin films composed of engineered nanostructures. GLAD combines a collimated vapor stream, low adatom mobility, and computer-controlled substrate motion. To form columnar thin films that can be sculpted into a variety of nanostructures, including vertically aligned nanorods, helices, and chevrons.

Hybrid Nano-CMOS Chips—Hewlett-Packard Laboratories www.hp.com

Field programmable nanowire interconnects (FPNI) consisting of 15-nm wide crossbar wires

combined with 45-nm CMOS have been demonstrated. They improve upon the FPGA architecture by lifting the configuration bit and associated components out of the semiconductor plane and replacing them in the interconnect with nonvolatile switches. This decreases the area and the power consumption of the circuit.

Invisicon Carbon Nanotube (CNT) Transparent Conductors—Eikos, Inc. www.eikos.com

Invisicon is a flexible transparent conductive coating based on single-wall CNTs that can be applied to any surface using traditional wet atmospheric coating processes. The coating is formed from dispersions of highly purified CNTs in a fugitive fluid. The resulting coating is more transparent than competitive systems, more flexible, has better abrasion resistance, and is stable to UV moisture and heat.

LithoParticles—Univ. of California at Los Angeles www.ucla.edu

LithoParticles are micro- or nanoscale fluorescent particles made from solid polymeric materials and dispersed in a liquid solution. The microparticles can be manufactured in any shape displaying "exquisite fidelity of the shapes." The researchers also claim to have the ability to make functional devices in solution.

Metal Infusion Surface Treatment (MIST)—C-3 International, LLC www.cccintl.com

MIST is an advanced, low-cost infused coating technology. The process takes any of 58 desired periodic table elements, or combinations thereof, into a formulation, which is then applied to non-organic materials. With a simple spray or dip and low heat treatment, the various elements and their unique properties are diffused into surfaces, along with a 0.1- to 0.5- μm infusion coating. The result is a uniform, durable nano-thin film treatment that delivers quantum physical improvements.

Metal Rubber Textiles—NanoSonic, Inc. www.nanosonic.com

These materials are novel, ultralow-weight, nearly transparent, electrically conductive, flexible textiles. They are made using an environmentally friendly, modified electrostatic self-assembly process. The materials are

nanocomposites that contain flexible polymers and electrically conductive metal nanoclusters. Included in the mixture are noble metals, metal oxides, and metal alloy nanoclusters, along with cage-structured molecules such as carbon nanotubes, buckyballs, and biomolecules.

Microcontact Insertion Printing—Pennsylvania State Univ. www.psu.edu

Microcontact insertion printing is a process for creating patterns of individual molecules on a surface that combines controlling self-assembling monolayers (SAMs) and soft lithography. The method builds surfaces that have molecules with specific functions inserted at known intervals on the surface.

Molecular Vapor Deposition (MVD)—Applied MicroStructures, Inc. www.appliedmst.com

MVD is a surface engineering technology whose primary benefit is that specific characteristics can be imparted onto a substrate without altering the bulk material traits. MVD is based on organic and metal-organic vapors in a low-temperature process which ensures compatibility with any material. MVD is suited for emerging applications where functional coatings act as surface lubricants in MEMS-based sensors and structures, as release layers for lithography, or to create reactive surface sites in bio-chips.

Nanocomposites via Epitaxial, 3-D Self-Assembly of Nanodots of One Complex Material within Another—Oak Ridge National Laboratory www.ornl.gov

Nanocomposites consisting of ordered 3-D arrays of nanodots of one complex ceramic material coherently embedded in another ceramic matrix comprise a novel class of materials for wide-ranging applications. Such materials are expected to exhibit novel physical properties tunable by adjusting the overall composition, concentration, feature size, and spatial ordering of the nanodots.

Nano eNabler System—BioForce Nanosciences, Inc. www.bioforcenano.com

The Nano eNabler system is a benchtop molecular printer for dispensing attoliter to

femtoliter volumes of various molecules for functionalizing biosensors and creating patterned surfaces. It is the first device designed specifically to print user-defined patterns of 1- to 30- μ m spots and lines onto a variety of surfaces with nanometer precision.

Nanogenerators—Georgia Institute of Technology

www.gatech.edu

These nanometer-scale generators produce continuous direct-current electricity by harvesting mechanical energy from such environmental sources as ultrasonic waves, mechanical vibration, or blood flow. The devices are based on arrays of vertically aligned zinc-oxide nanowires that move inside a novel zig-zag plate electrode. They take advantage of the unique coupled piezoelectric and semiconducting properties of the zinc-oxide nanostructures.

Nano Imprint Lithography (NIL) Equipment, NPS300—SUSS MicroTec Lithography GmbH

www.suss.com

NIL exists in two methods—UV-NIL and hot embossing. Both methods consist of printing a mold/stamp with nm-features onto a polymer, thus transferring the stamp pattern into that material. Curing of the polymer is then performed with either UV light or temperature. The uniqueness of the NPS300 equipment is in the fact that it can handle both technologies without any tradeoffs or shortened changeover capabilities.

Nano Indenter G200—MTS Systems Corp.

www.mtsnano.com

Nano Indenter G200 is a next generation nanomechanical testing system. While typically used to perform nano indentation tests, the system also is capable of quantitative nanomechanical microscopy (3-D topography), scratch and adhesion testing, microhardness testing, and mechanical testing of MEMS devices and structures. The system employs electromagnetic actuation as the core technology.

nano-TA—Anasys Instruments

www.anasysinstruments.com

nano-TA is the first ever product that enables quantitative local thermal analysis at the sub-100-nm size scales. The nano-TA module allows any atomic force microscope to perform these local thermal analyses. The device

functions as a normal imaging AFM with a resolution of better than 30 nm, and, upon choosing a region of interest, the user can reposition the probe tip and subject the region to a thermal ramp.

nanoTensile 5000 Automated Test Instrument—Hysitron, Inc.

www.hysitron.com

The nanoTensile 5000 is an automated, 3-D sensing, nanometer-scale precision tensile instrument for the testing of small-scale material specimens and miniaturized devices. This instrument provides a 3-axis load measurement and is isolated from external force and acoustic and thermal disturbances. Its displacement resolution is five times better than the next best system.

Nerve Graft Materials—Univ. of California at Berkeley

www.berkeley.edu

Nerve graft materials composed of aligned, nanoscale polymer fibers that act as physical guides for regenerating nerve fibers have been developed. These nanofibers become bioactive by attaching various biochemicals directly onto the surface of the nanofibers. The technology has been licensed to NanoNerve, Inc.

Non-reflective Coating—Rensselaer Polytechnic Institute

www.rpi.edu

Three titanium dioxide nanorod layers and two silicon dioxide nanorod layers placed via oblique-angle deposition on the surface of a transparent sheet of aluminum nitride result in a coated material that reflects virtually no light. The thin films are progressively layered more densely such that the boundary layers are more gradual, reducing the reflection of light.

NS Gold Oxidation Catalyst Technology—Nanostellar, Inc.

www.nanostellar.com

NS Gold is used as a coating in automotive catalytic converter systems to reduce noxious emissions by 40% more than traditional pure platinum catalyst materials at an equal cost. To develop the gold-platinum-palladium-based NS Gold, the performance of nanoscale materials in diesel emission control applications was targeted and refined using a combination of computational modeling and a rapid synthesis-analysis cycle.

PRINT Technology for Engineered Drug Therapies—Liquidia Technologies, Inc.

www.liquidia.com

PRINT is a nanoparticle fabrication technique that allows for the precise control over particle size, shape, composition, modulus, and particle surface properties. PRINT nanoparticles have been manufactured containing biological, small molecular, and imaging agents. By expressly engineering the surfaces for cell and tissue recognition, the nanoparticles can target certain cell and tissue types.

RainMaker Humidification System (RHS)—RASIRC

www.rasirc.com

This is the first and only system to generate and deliver precise amounts of ultra-pure water vapor purified for both ionic contaminants and dissolved gases. Utilizing a non-porous membrane that excludes particles, micro-droplets, volatile gases, and other opposite-charged species, the RHS adds controlled amounts of ultra pure water vapor directly into any carrier gas stream.

Self-Assembling Process for Fabricating Tailored Thin Films—Sandia National Laboratories

www.sandia.gov

This simple, economical nanotechnology coating process enables the development of nanoparticle thin films with architectures and properties unattainable by any other processing method. This nanoparticle surface chemistry enables dispersal in readily available commercial solvents, allowing easy and rapid production of films through spin, dip, or spray coating under ambient conditions.

Super CNT Fibers—Los Alamos National Laboratory

www.lanl.gov

Spun from 1-mm-long, double-wall carbon nanotubes (CNTs), Super CNT Fibers have 10% of the density, and four to five times the specific strength and specific stiffness of the best carbon fibers now used to make structural composites. CNT yarns have been directly spun from CNT arrays, providing good alignment and high CNT volume fractions.

INDUSTRY REPORT

Current MEMS Challenges



Patric Salomon



Henne van Heeren

If someone had asked MEMS analysts 10 years ago what the big challenge in MEMS was, most would have answered commercialization. Although technologically promising, MEMS were difficult to sell: the technology was not proven, there was no reliable infrastructure, and only a few people understood the potential and were able to link the technology with a specific application.

Five years ago, the biggest issue was seen to be the industrialization of MEMS technology and more specifically their packaging and integration. Laboratory models were difficult to translate into high-volume and low-cost production concepts.

Today, these issues have mostly been solved. Many MEMS devices are now on the market, and both specific and generic MEMS packages are increasingly becoming available. This is good news for the supply chain: MEMS equipment suppliers and MEMS foundries are doing well.

However, the MEMS industry is still confronted with significant questions:

- Is second sourcing for MEMS production feasible?
- Is it time for (generic) MEMS technology roadmaps?
- Does it make sense to create MEMS standards?
- Can we define core reliability issues and agree on a common design methodology?

• Consumer and automotive MEMS are making use of only a few generic technologies and a limited set of substrates. Will that be the future for microfluidics and other applications as well?

These issues are interlinked and relate to two major drives: minimizing risk in outsourcing and minimizing risk in development of new products and more specifically the new equipment.

At a recent meeting of the MEMS Industry Group, METRIC 2007, in Pittsburgh, Pa., 70 MEMS technologists and business leaders discussed these issues. The main organizations driving this discussion are the end-users of MEMS products and equipment suppliers. Foundries are also participating, as it is in their interest to create standards close to their respective abilities and technologies.

Why are these issues difficult to tackle? The initial problems in the supply chain were solved through bilateral cooperation between suppliers and (potential) customers. The issues posed now have to be tackled through cooperation between competitors, through an open exchange of information, and by agreeing on development targets to fit industry-wide accepted roadmaps and standards.

But even without a roadmap or standards, a convergence of technologies can be seen. Take, for instance, the packaging for accelerometers. Although not all accelerometers are precisely interchangeable, they look much more alike than 5 years ago. Similar observations can be made for equipment. Suppliers look into each others' products and take care that their equipment matches interfaces and basic performance. This is a good start for the development of roadmaps and standards, partly formal agreement, partly mutual silent agreement, and partly hard work of industry organizations such as MEMS Industry Group, Nexus Association, and MANCEF.

MEMS successfully penetrate into new market segments, and again one can see potential users hesitating, suppliers uncertain about time scales, and a certain mismatch between industrial demands and MEMS technology offers. So where does this all lead?

A common theme that evolved from the METRIC working groups is that strong communication among each link of the MEMS supply chain is crucial to the success of the MEMS industry. There's a great need for the industry to continue to come together (in-person and virtually) and communicate their needs and requirements to one another.

—Patric Salomon,

4M2C PATRIC SALOMON GmbH, Germany

—Henne van Heeren, EnablingM3, The Netherlands

Buckyballs fight allergies

Buckyballs (C_{60}) that suppress allergic response and basic immune reactions in human mast cells (MCs) has been reported by Christopher Kepley, Virginia Commonwealth Univ. Health Systems, Richmond. The buckyballs reduce the activation of signaling molecules that are involved in mediator release and oxidative stress. Potential applications are in controlling MC-dependent diseases like asthma, inflammatory arthritis, heart disease, and multiple sclerosis.

Virginia Commonwealth Univ., www.vcu.edu

Bursting bubbles move fluid

Cavitation in a microfluidic device that accelerates and mixes fluid has been demonstrated by Claus-Dieter Ohl, Univ. of Twente, the Netherlands. Cavitation (bubble dynamics) is created by focusing a pulsed laser into bubbles that are filled with a light-absorbing liquid. At the center of a 20- μm thick and 1-mm wide channel of the device, pancake-shaped bubbles expand and collapse radially. When a bubble is created close to a wall, a liquid jet is focused towards the wall. Here, the jet flow creates two counter-rotating vortices, which stir the liquid at high velocities.

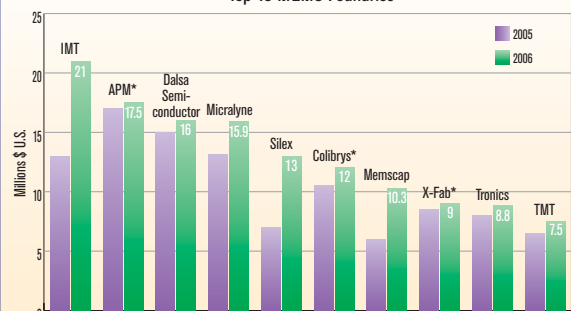
Univ. of Twente, www.utwente.nl

Bacteria carry nanoparticles

Bacteria-mediated delivery of polystyrene (PS) nanoparticles to cells, which precisely deliver diagnostic or therapeutic cargo, has been reported by Rashid Bashir, Purdue Univ., West LaFayette, Ind. In the work, PS nanoparticles that are linked to DNA are attached to the outside of bacteria. Then the nanoparticle-laden bacteria transport the DNA to the nuclei of human cancer cells. The cargo-carrying bacteria attaches to the recipient cell and is engulfed by the cell's outer membrane, forming vesicles, which are drawn into the cell's interior. Simultaneously, the PS nanoparticles (40- to 200-nm dia) release their cargo.

Purdue Univ., www.purdue.edu

Top 10 MEMS Foundries



*WTC estimate dedicated MEMS fabs only, does not include ST or Sony

Source: WTC

MEMS BRIEFS

Move micromachines remotely

The Casimir force that is changed using a beam of light, enabling the remote operation of micromachines, has been reported by Umar Mohideen, Univ. of California, Riverside. Here, the optical modulation of the Casimir force is demonstrated through a change in the carrier

density by the absorption of photons. In the work, light from a 514-nm argon (Ar) laser is segmented into 5-msec pulses, irradiating a Si membrane that is mounted on top of a piezo that can travel up to 6 μm between the membrane and gold (Au)-coated polystyrene (PS) sphere (~200 μm dia). The light beam

changes the membrane's carrier density by an amount that is enough to modulate the Casimir force between the membrane and the sphere.

Univ. of California, Riverside, www.ucr.edu

New standards

Six new technical standards that apply to the semiconductor, flat panel display (FPD), and MEMS manufacturing industries have been announced by SEMI, San Jose, Calif. SEMI D50 provides guidelines for measuring the surface hardness of a polarizing film and its materials for FPD production that apply to manufacturing, quality control, and R&D work. SEMI M71 relates to the selection and purchase of SOI wafers for CMOS LSI (complementary metal-oxide semiconductor large-scale-integration) 130-nm technology and beyond in which vendors use guidelines to provide correct specifications of wafers that are suitable for an application.

SEMI, www.semi.org

Top 10 foundries

Updated MEMS foundry rankings have been provided by Yole Développement, Lyons, France. The top MEMS foundries/contract manufacturers in ranked order that reached total sales of \$157 million in 2006 are: Innovative Micro Technology (U.S.); Sony Corp. (Japan); APM (China); Micralyne Inc. (Canada); DALSA Semiconductor (Canada); Silicon Microstructures Inc. (U.S.); Memstech (Malaysia); Colibrys (Switzerland); Silex Microsystems (Sweden); MEMSCAP Inc. (U.S.); and Tronic's Microsystems (France).

Yole Développement, www.yole.fr

MEMS partnerships

A cross-licensing arrangement between Knowles Akustica, Itasca, Ill., and Pittsburgh, Pa.-based Akustica Inc. will strengthen each company's patent portfolio. The terms of the agreement have not been disclosed, however, the partners will not have restrictions on sales of products from either company. And, Switzerland-based chip maker STMicroelectronics will see sales growth at its MEMS-business unit as it is a key provider of MEMS units for the Apple iPhone and iPod. Apple will ship up to 8 million iPhones and 35 million iPods in the second half of 2007, which will at least double STMicroelectronics' MEMS unit sales.

Knowles Akustica, www.knowlesacoustics.com
STMicroelectronics, www.st.com



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MICRO NANO

Nanoinjector does not damage membrane

A nanoscale cell injection system called nanoinjector that uses carbon nanotubes (CNTs) to deliver cargo into cells without plasma membrane damage has been demonstrated by Carolyn Bertozzi and Alex

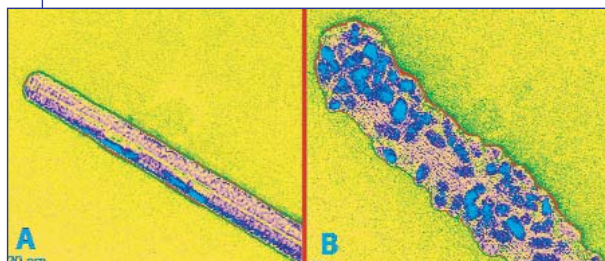
Zettl at the Univ. of California, Berkeley. The cargo consists of quantum dots (QDs; 50- to 100-nm dia) in which the QDs' surfaces are coated with streptavidin. The disulfide bond is sandwiched between a pyrene section on one side and a biotin section on the other. The pyrene adsorbs to the MWNT, while the biotin binds to the bacterial protein streptavidin.

An AFM integrated with an inverted fluorescence microscope serves as the nanomanipulator. The AFM controls the nanoneedle as it penetrates the cell's plasma membrane. Here, the disulfide bonds within the cell, releasing the cargo inside the cell's cytosol within 15 to 30 min. Finally, the AFM retracts the nanoneedle.

A key advantage of this biocompatible nano-injection technology is that the process can be performed many times or simultaneously with other measurements throughout the normal life cycle of the cell.

Future work will focus on combining the AFM and a chemical force microscope (CFM) to carry out organelle-specific nano-injections, enabling probes into plasmid DNA, or carry out parallel nano-injections of different cell sites with different probes.

Univ. of California, Berkeley, www.berkeley.edu



A) An MWNT-AFM tip is seen before loading the cargo. **B)** The tip is coated with linker 1 and conjugated with QD-streptavidin. Source: Proceedings of the National Academy of Sciences.

Zettl at the Univ. of California, Berkeley. This technology consists of three key components: a needle, a manipulator, and a controllable means of loading and releasing cargo.

In the process, a single multi-walled carbon nanotube (MWNT; 1-nm dia) is attached to an AFM tip, which acts as the nanoneedle. The needle is function-

New coalition

The Synthetic Organic Chemical Manufacturers Association (SOCMA), Washington, D.C., formed the Nanotech SME Coalition for start-ups and small- and medium-sized enterprises that develop and manufacture nanoscale materials. This coalition will provide a perspective on health, safety and environmental aspects of nanotechnology to the Environmental Protection Agency (EPA), the Occupational Health and Safety Administration (OSHA), and the Food and Drug Administration (FDA).

SOCMA, www.socma.org

Superalloy materials

Processes that use radiolysis to break down the molecular structure of substances to form superalloy nanoparticle compositions are being developed by Tina Nenoff, Sandia National Laboratories, Albuquerque, N.M. In one experiment, solvent molecules are combined with molecules or ions, dissolved in water, and then subjected to radiolysis. By varying the reaction conditions and using alcohols as agents to limit particle growth size, the grown nanoparticles are nearly identical, delivering defect-free superalloy metal nanoparticles.

Sandia National Laboratories, www.sandia.gov

Ultraviolet LEDs

Gallium nitride (GaN) light-emitting diodes (LEDs) made from nanowires that emit ultraviolet (UV) light have been reported by Abhishek Motayed, National Institute of Standards and Technology (NIST), Gaithersburg, Md. Electric field-assisted alignment places n-type GaN nanowires on a p-doped GaN sapphire surface. The nanowire/epilayer p-n junction diodes are passivated with a layer of silicon dioxide (SiO₂). The p-n junctions display an electroluminescence with a 365-nm peak wavelength. The UV LEDs display excellent thermal stability (temperatures up to 750°C) and operational stability.

NIST, www.nist.gov

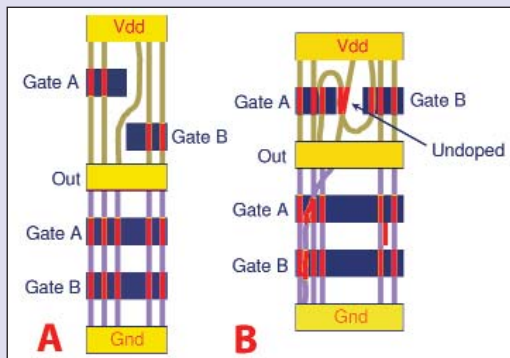
Circuit works with misaligned nanotubes

An algorithm that determines whether a carbon nanotube field-effect transistor (CNTFET) provides correct logic functions, even in the presence of a large number of misaligned CNTs, has been reported by Subhasish Mitra at Stanford Univ., Calif. By using this mathematical approach, misaligned-CNT-immune circuits automatically generate designs that are guaranteed to be immune to incorrect logic function.

In the work, two NAND (NotAND) circuit designs are used—one has two gates in a pull-up network that are not on the same plane while the other circuit has both gates at the same horizontal level, which are separated by an undoped area. (Here, the CNTs in the undoped area can be etched away.)

In fig. A, the circuit has misaligned CNTs in the dope areas, which causes a short, but in fig. B, a short does not occur with these misaligned CNTs since they pass under the two gates or go through the undoped area. The CNTs do not conduct unless a gate is ON.

To develop the algorithm, the circuit is divided into a square grid in which each square is a node within a graph. The graph indicates the various regions within a grid (contact, doped area, etc.). The algorithm combines complex network mathematics and Boolean algebra to define regions on a batch of CNTs. This algorithm automatically determines where the legal and illegal regions should be in the design of a circuit



A) Misaligned CNT-vulnerable NAND cell **(A)** and a misaligned CNT-immune NAND cell **(B)** are shown. Source: Subhasish Mitra, Stanford Univ., Calif.

element with a particular function. To eliminate unwanted CNTs that cross a boundary into another square of the grid, they are etched away so they do not conduct an erroneous current to another transistor.

While this work solves the misalignment problem, other challenges remain such as controlling the density of CNTs and reducing the yield of CNTs that act as a metal (currently ~30%) from one batch to the next.

Future work will focus on fabricating and testing real circuit elements according to the algorithm's output.

Stanford Univ., stanford.edu