

# Nano-Manufacturing: Technical Advances, Research Challenges and Future Directions

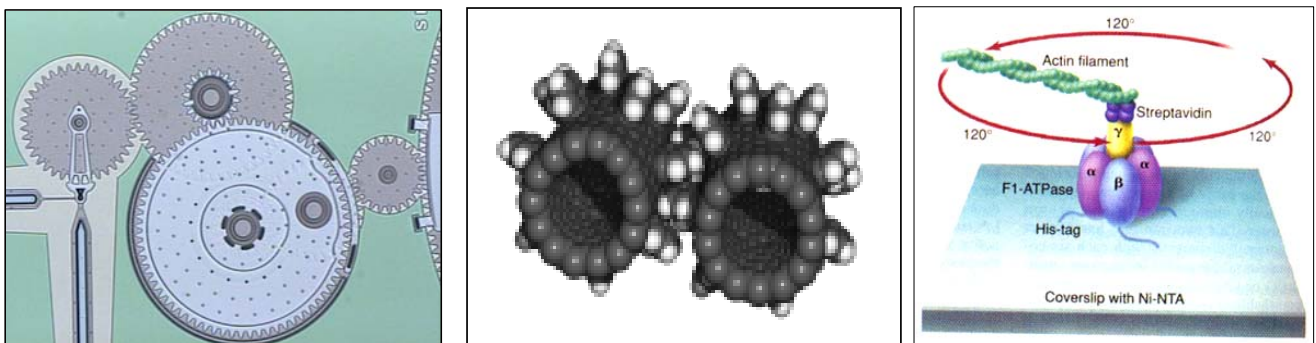
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## **Abstract**

This article provides a review of the nascent field of manufacturing at the nanoscale, tracing its roots to the promise of nanotechnology for serving the society through valuable products and services. A comprehensive representative set of nanoscale technologies in processes, materials, pharmaceuticals, electronics, instruments etc. that have reached or are currently introduced to mass production is presented, and the key technological advances that led to their development are identified. This points to promising new research directions and the requisite infrastructure needs in nanomanufacturing, oriented towards enabling scalable technology transfer to industry and emphasizing producibility, predictability and productivity aspects. International efforts in this arena are overviewed, with further insight into the related recent activities of the National Science Foundation in the USA.

## **Introduction**

The ability to manufacture and use materials, devices and systems integrated from the nanoscale is one of the most important promises of nanoscale science and engineering. New paradigms are expected in industry, economy, healthcare, environment and security. As an example, gears have been studied and used for millennia as a macroscale mechanism to transmit mechanical power and information (Fig. 1, [1]). However, carrying the design of a gear transmission to the nanoscale is challenged not only by dominant effects of their high surface/volume ratio, and the problems of friction, stiction, surface tension, electrostatic forces etc. during operation, but also by major hurdles in their manufacturing at the nanoscale in a repeatable, economical and high rate for industrial production. At the same time, nature offers robustly producible, effective molecular mechanisms, such as the actin-myosin filament walk-along interactions in our muscle fibers for linear motion [2] and F<sub>1</sub>-ATPase biomotor for rotational motion [3]. Such biomimetic paradigms open up exciting research opportunities not only in the analysis of biological archetypes for generating physical movements, but also in the design and manufacturing of bio-inspired devices and their large-scale production for efficient and reliable transmissions at the nanoscale.



**Fig. 1.** a. Microscale gear (Sandia National Labs, 1990); b. Nanoscale gear (E. Drexler - simulation) c. Biological nanomotor (H. Noji, Science 1998)

Principles of mechanical, thermal and fluid sciences were developed since the Greek-Roman antiquity. Heron of Alexandria (1<sup>st</sup> century AD) describes in his *Pneumatica* a working prototype of the *aeolopile*, the precursor of both the steam engine and the jet turbine (Fig. 2, [4]). Yet their first implementation during the industrial revolution had to be postponed for almost eighteen centuries, because of the necessary progress in engineering aspects (combustion, insulation, lubrication, bearings), and particularly in the manufacturing research and infrastructure (mass-production casting, forging, machine shop equipment). Today, manufacturing is on the verge of a new technological revolution, starting by controlling structural arrangements at the atomic and molecular level. The transition from vision advanced by Demokritos (4<sup>th</sup> century BC) and Feynman (1959), and the first tool, the scanning tunneling microscope (STM), to monitor atoms on a surface [5] and to manipulate and position individual atoms [6], to industrial manufacturing will be much shorter. The vision that by using molecular interactions and specific phenomena and processes at the nanoscale one can develop highly efficient manufacturing methods [7] is advancing fast to reality, on various rates as a function of the area of relevance. Recent workshops, e.g. one jointly sponsored between the National Science Foundation and the European Commission [8], have recognized nanoscale manufacturing as the crucial step to be taken towards such an achievement. In the meantime, a first generation of nanotechnology products such as nanostructured dispersions, coatings and materials is already on the market.



Fig. 2. Reconstruction of Heron's Aeolopile (ca. 80 AD)

The objective of this review article is to provide an overview of current scientific and technological advances in nanomanufacturing, in the context of nanotechnology products, processes and tools that have reached or are currently at the commercialization stage. Although the list of such case studies can not be exhaustive, representative research breakthroughs in manufacturing that enabled such advancements are emphasized in this framework. This is followed by a projection of outstanding research challenges to be faced in order to realize further progress in nanomanufacturing, as well as certain key research goals and resource needs.

### **Current State of the Art**

Nanoscale manufacturing encompasses all materials, processes and equipment aimed toward building of nanoscale structures, features, devices, and systems in one, two and three dimensions. It melds both bottom-up assembly of nanostructure building blocks with top-down processes for economical devices and systems with complex functions.

Manufacturing techniques at the nanoscale have equal relevance as novel components of traditional industries, and as engines for revolutionary technologies enabling new products and services. They promise to increase in quality, productivity and efficiency of existing technologies, and to establish

industries and markets that would have not been possible otherwise. Advances in manufacturing at the nanoscale are anticipated to accelerate commercialization of products such as: nanostructured materials with novel and improved properties; information technology nanodevices including advanced semiconductors, molecular electronics and spintronics; nanobiotechnology and pharmaceuticals – diagnostics, implants, new drugs and their therapeutic delivery; measuring devices and tools for manufacturing; higher performance safety and security technology including sensors, adsorbents, filters and decontaminants; and nano-electromechanical systems (NEMS).

Illustrations of such industries to benefit from nanoscale manufacturing technologies are:

- *Advanced materials* for improved physical, chemical and biological properties. Examples are to be found in materials and tools industries, chemical, construction, textile and other industries. Such materials will include catalysts, nanostructured polymers, non-woven fabrics from electrospun nanofibers; strong and lightweight nanoparticle, nanotube or nanofiber-reinforced polymer composites and metal alloys; nanoporous polymer and metal foams; nano-grained superhard coatings for machine tools, molds, dies and instruments; superplastically deformable nanopowder-consolidated metals and ceramics for shape forming; smart materials with embedded conductive, piezoelectric, magnetostrictive, shape memory alloy or magnetorheological elements for color, texture, conductivity control and sensory or active behavior etc.
- *Electronics, information technologies and communications industries.* Examples include: molecular or nanostructured switches, amplifiers and interconnects for analog/digital data processor and storage devices, including single-electron, spin and magneto-electronics and hybrid technologies; DNA computation platforms; liquid crystal and photonic flat/flexible panel displays, audio and haptic devices and sensors; photonic crystals for optical signal processing in fiber communications; nanostructured wireless transmitter/receiver microdevices for local (RF) tag identification, or satellite localization (GPS) etc.
- *Pharmaceutical, biochemical, food, power and environmental remediation industries.* Examples are chemical/drug screening arrays; microbial, viral and toxic gas and food sensors for warfare defense and emission control; nanostructured catalysts (on zeolites, aerogels, hydrogels etc) for reactors; colloidal micelles and nanograined films, inks, paints, fire-retardant/resistant coatings etc; nanoparticle dispersions and aerosols; consolidated nanoparticle or nanostructured proton exchange membranes for fuel cells; filtration membranes for desalination and pollution control; nanostructured cells for flexible photovoltaics, artificial photosynthesis, new types of batteries etc.
- *Medical, health and safety industries.* Examples are through drug/gene bioassay arrays for genomics and proteomics research and clinical therapy; nanoparticle and nanosphere medication/gene vectors; nanostructured biomaterials (hydroxyapatite, calcium phosphates) for implants and prosthetics; implantable aid microdevices such as programmable medication dispensers, pacemakers, pressure/glucose detectors etc; sterile surface catheters, surgical tools, and nanoparticle agent and sensor technologies for medical imaging; nanostructured biocompatible/biodegradable scaffolds for artificial tissue engineering and regenerative medicine etc.
- *Aerospace, automotive and appliance industries,* through high strength/weight ratio nanostructured alloy and composite materials for fuselage, body and other structural elements; highly resistive or ultra-low friction layers for thermal barrier coatings, bearing surfaces etc. in jet, internal combustion, and hydraulic/pneumatic engines and elements; nanostructured microelectromechanical systems (MEMS and NEMS) such as accelerometer and gyroscopic sensors or fuel injection and supplementary restraint fluidic actuators, reconfigurable control surfaces, etc.

- *Service industries*, including the users of nanomanufactured products. These span nanostructured and nanofabricated product design and prototyping companies; market analysis and marketing of such products; research and development laboratories and consulting firms; intellectual property development and management services for nanomanufacturing technologies; related education at the technical school or college /university level; workforce training of professionals for nanomanufacturing industries; software development for product design, process simulation, modeling and control, continuous learning etc.

### Nanomanufacturing Case Studies

#### **1. Sintering of nanoceramics and nanocomposites by plasma pressure compaction [9]**

A new powder consolidation technique has been developed for compaction of submicron powders and nanopowders of metals, intermetallics and ceramics, which can also be used as an alternative to hot isostatic pressing of micron particles. *Plasma Pressure Compaction (P<sup>2</sup>C)* uses plasma to break surface oxide and impurity layers of sintered powders and to partially provide the activation energy for micro/nanobonding of the cleaned core material of the particulates. This results in reduction of the necessary processing temperature, which is essential to prevent grain growth in consolidates and thus to preserve the nanoscale properties of particulates in the part. It also improves the consolidation density and reduces oxygen and other gas contamination in the product, without the need for sintering additives and precompaction of a green part. The process can also be used for reactive joining of dissimilar materials and reactive synthesis of near net shape parts, such as carbon-carbon composites for high strength/weight ratio and temperature- and corrosion-resistant materials for engine pistons etc. Such products can provide essential benefits for fuel economy, maintenance and pollution and noise prevention.



Fig. 3. P<sup>2</sup>C device (courtesy Materials Modification Inc).



Fig. 4. C-C composite piston (Detroit Diesel)

#### **2. Transparent nanopowder dispersions [10]**

New mechanical grinding, milling, alloying, mixing and dispersion technologies have been transferred to production of nanopowder-laden dispersions and suspensions, such as crèmes for pharmaceuticals and beauty products. These methods, employing surface functionalization and electrical charging of particulates, cope with aggregation problems of the nanopowders into clusters, and thus minimize the effective size and maximize the active surface area of the particles. An example is sunscreen crèmes with dispersed ZnO and TiO<sub>2</sub> nanoparticles (about 100 nm), which absorb and scatter ultraviolet radiation twice as effectively as traditional products, while they minimize interference with visible wavelengths, thus resulting in a transparent ointment preserving the original appearance of the substrate. Other applications include paints, additives and varnishes.

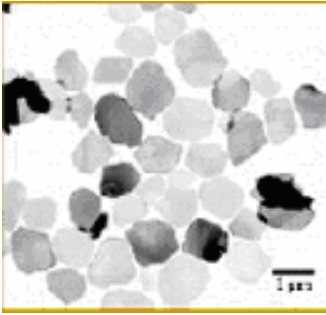


Fig. 5. ZnO powder dispersion in a sunscreen (courtesy Elta Block).

### 3. Non-woven fabrics from electrospun nanofibers [11]

Electrospinning of plastic and ceramic nanofibers, through a rheological instability of charged polymer melt droplets in an intense electrostatic field, has been scaled to industrial production of nanofiber products. The nanofibers, featuring 10-100nm diameters and macroscale lengths, are 2-3 orders of magnitude finer than traditional textile fibers and human hair, and can be made of a variety of nylon, polyesters, polyamids, acrylics etc. as well as biomolecules of proteins, collagen etc. Randomly laid aggregates of nanofibers in non-woven bundles, membranes and bulk structures exhibit high porosity, small interstitial size, high surface area resulting in high absorbency and reactivity to chemically functional groups. Typical applications of nanofiber threads and paper-like membranes are in barrier fabrics, filtration products and biomedical devices. These are used for thermal insulation, energy storage, lightweight structural composites, high retention filters, and potential bandage and diaper products.



Fig. 6. A human hair in a nanofiber background (courtesy eSpin Technologies)

### 4. Molded nanocomposites for automotive parts [12]

Much progress has been achieved in industrial production of automobile parts, made of injection-molded polymer nanocomposites with clay nanofillers. This has recently extended to low-cost thermoplastic polyolefin (TPO) resins which previously were reinforced with microscale talc particles, glass or carbon fibers. New manufacturing technologies have enabled the exfoliation of smectite clay fillers into nanoflakes, about 1 nm thick and 100-1000nm long, as well as their dispersion in the polymer avoiding aggregation phenomena, thus maximizing the interaction surface with the matrix and the reinforcing effects. Thus, low smectite filler contents (2.5-3%) of TPO nanocomposites can yield up to 20% weight savings at similar stiffness (1000-1200 MPa) and improved low-temperature ductile strength compared to traditional TPO composites (with 15-20% talc content) of the same cost. The nanocomposites display improved throughput, paint adhesion and recyclability because of the smaller filler amount. Injection molding at lower pressure, reduced cycle times and appearance defects is used in production for nanocomposite step-assist parts in vans while rocker panels, sail panels and body claddings are considered.



Fig. 7. Nanocomposite step-assist for vans (courtesy GM/Blackhawk Automotive Plastics)

### 5. Abrasion resistant and hermetic nanocomposite coatings [13]

Nanocomposite polymer coatings with nanopowder additives are commercially co-extruded or bonded to a variety of substrate materials, providing superior abrasion resistance, up to four times of conventional scratch-proof coatings. Cross-linking and reinforcement mechanisms of the polymer chains of the coating matrix by the nanoparticulates withstand mechanical ploughing and chemical action effects. At the same, the nanoparticle size and dispersion controls selective absorption and scattering of visible light, providing clear coatings with customized optical properties, i.e. anti-reflection and tailored refractive indices, with applications in helmet visors, aircraft canopies, and smart windows. Besides impact resistance, the same mechanisms in such nanocomposites also yield improved oxygen and moisture diffusion barriers, making them suitable for hermetic food and beverage packaging, noble and light gas containers (e.g. in athletic shoes), and pharmaceutical push-through packages, because of their high manufacturability and recyclability standards.



Fig. 8. Nanocomposite coatings in helmet visors, pharmaceutical packages and food containers (courtesy Triton Systems Inc.).

### 6. Jumbotron lamp [14]

Recent progress in manufacturing of oriented carbon nanotube-covered surfaces by plasma enhanced chemical vapor deposition (PECVD), pulsed laser deposition (PLD) etc. has enabled harnessing their unique electron emission properties. In a diode configuration, a cathode ray tube (jumbotron lamp) has been commercialized, producing light by bombarding a phosphor-coated surface by nanotube-emitted electrons, featuring twice the brightness of thermionic lighting elements, and lifetimes up to 8000h. The required low applied voltage yields improves energy efficiency, and the lamp can be used for illumination and large outdoor displays. Carbon nanotube field emitters with current densities over  $0.1 \text{ A/cm}^2$  are under development for microwave amplification to replace unreliable thermoelectronic emitters, and for overvoltage protection in a gas discharge tube arrangement (Rosen et al). Further research is under way to improve manufacturing aspects of nanotube field emitters and gated triode microdevices, including lifetime, yield and cost.



Fig. 9. A nanotube-based jumbotron lamp (courtesy Y. Saito)

### **7. Nanotube field emitters and displays [15]**

Approaching commercial manufacture are flat panel displays based on nanotube field emission, offering a potentially advantageous alternative to thin film transistor (TFT) screens in terms of brightness and power efficiency. To date, a 9" full color field emission display with 576x242 addressable pixels in diode configuration has been demonstrated (Wang, Choi et al). Besides emission from nanotube assemblies, the monochromatic electron emission from single multi-wall carbon nanotubes (MWNT) has been demonstrated in high-resolution electron beam instruments. A low energy electron projection microscope with a highly coherent beam between a single MWNT emitter and the sample was developed (Fink et al) for acquisition of in-line electron holograms of the target, with quality comparable to atom-sized W emitters. Manufacture and integration of carbon nanotube emitters for field emission electron microscopes is also under active research.

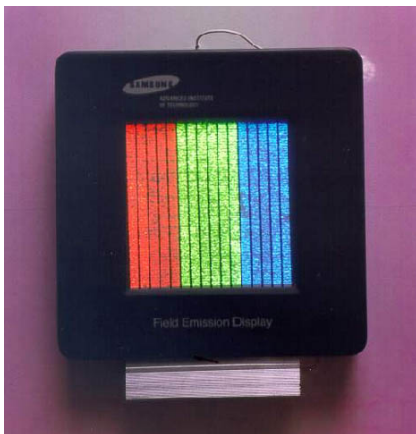


Fig. 10. A 4.5" nanotube field emission display (courtesy Samsung Electronics)

### **8. Molecular electronic memory and logic [16]**

Recent advances in imprint nanolithography and self-assembled monolayer (SAM) fabrication bring molecular electronics closer to commercialization for memory and logic circuitry, as a competitor to silicon platforms. Such a prototype 64-bit molecular electronics memory (on a <1 square micron area) with demultiplexer logic has been demonstrated (Williams et al). A grid master (fabricated by optical and electron beam lithography) imprinted 40 nm wide parallel trenches on a polymer layer of a Si wafer for platinum nanowires, on which an electronically switchable molecular layer (e.g. rotaxane) was sandwiched with a second orthogonal set of nanowires in a cross-bridge arrangement. Such molecular electronics-based static random access memory (SRAM) is non-volatile, and promises more than an order of magnitude higher capacity and performance than silicon memories, possibly on multi-layer structures, and with potentially lower manufacturing costs.

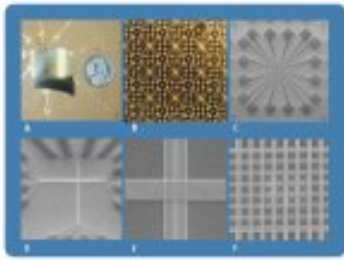


Fig. 11. A 64 bit molecular electronic memory prototype (courtesy HP).

### **9. Probe array nanofabrication [17]**

Large arrays of cantilever probes, thermomechanically inducing quantum dot indentations in thin polymer films, such as the Millipede project (P. Vettiger, G. Binnig et al), have been developed and used for ultra-high density data storage (1 trillion bits per square inch, equivalent to 25 DVDs on a postage stamp area, and 20 times higher than magnetic storage). Prototype 2-D arrays under development feature over 4000 (64x64) V-shaped tips ( $2\ \mu\text{m}$  long) on  $70 \times 0.5\ \mu\text{m}$  Si cantilevers, arrayed over a  $7\ \text{mm}^2$  field. Each tip produces indentations  $10\ \text{nm}$  in diameter through resistive heating and deformation of thermopolymer films, at kHz to MHz frequencies and very low power consumption. The arrays feature accurate levelling, vibration damping, and precision electromagnetic x-y scanning motion with respect to the processed medium, as well as time-multiplexed electronics for addressing the probes. Besides its suitability for high resolution and high rate flexible continuous patterning, the Millipede technology also features reversible erasing/rewriting capabilities for dynamic reshaping and error correction, as well as thermoresistive in-process sensing of the surface topology, making it appealing as a generic planar nanostructure fabrication tool with feedback control. Potential applications include mask-less thermomechanical nanolithography, atomic and molecular quantum nano-manipulation, large-area nanoscopic imaging etc.

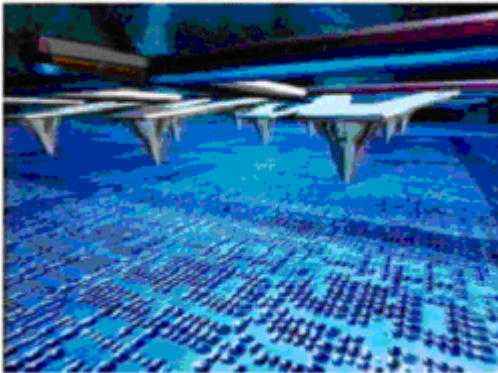


Fig. 12. Millipede nanopatterning (courtesy of IBM).

### **10. Sputtered GMR spin valve heads for magnetic recording [18]**

Besides the discovery of the giant magnetoresistive (GMR) effect in Europe in 1988 (P. Gruenberg and A. Fert) in epitaxially grown multilayer films at cryogenic temperatures and high magnetic fields, realization of a functional GMR spin valve head in 1997 at room temperature, reasonable magnetic field intensity and made of affordable materials, was made possible by their productive fabrication by sputtering (S. Parkin, IBM Almaden Research Center). This involved addressing of key manufacturing issues, such as dimensional precision and repeatability of the sputtered multiple layers, uniformity of material properties for reproducible resistance changes in operation, stability over the device lifetime, and production reliability and costs. This provided a disruptive technology for magnetic disk drives of superior storage capacity on the market, over 95% of which today employ GMR spin valve heads.

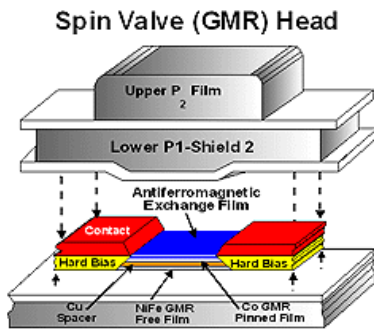


Fig. 13. A GMR spin valve head for magnetic recording (courtesy IBM).

### 11. Electron Beam Lithography fabrication integrated to electronic microscopy [19]

Affordable fabrication of master patterns with nanoscale features for mass manufacturing processes, such as imprinting and patterned bottom-up methods, by electron beam nano-lithography (EBL) was greatly promoted by the introduction of EBL add-on attachments to widespread electron microscopes, such as scanning electron microscopy (SEM) and focused ion beam (FIB) instruments. The combination of the EBL nanowriting capability with in-process, in-situ nanoscale imaging, in small scale step-and-repeat exposures, enhanced dramatically real-time process monitoring and control, and improved resolution, repeatability and fabrication rates of tools and devices, such as quantum wire/well structures and prototype transistors.

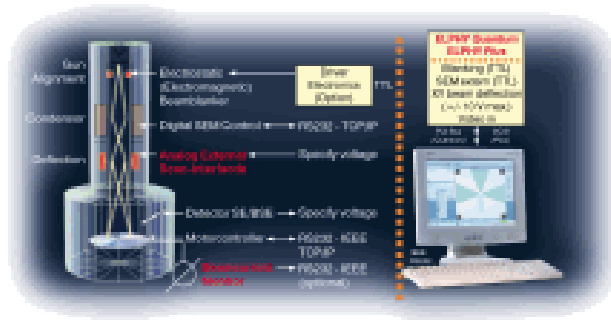


Fig. 14. A SEM/EBL system (courtesy Raith GmbH)

### 12. Nanoscale imprinting lithography [20]

Mechanical imprinting nanolithography methods, through contact printing and embossing under proper temperature and pressure, can stamp or impress nanoscale patterns with features as small as 10 nm on heat-hardenable or ultraviolet-curable materials, and can provide a lower cost alternative to diffraction-limited photolithography processes for microelectronics, MEMS, biofluidic devices etc. Such methods include nanoimprint lithography (NIL), step and flash imprint lithography (SFIL), nano transfer printing (nTP) etc, and respective commercial systems are already on the market and tested in production applications. At the same time, research is under way to resolve the requisite needs for surface planarity and layer alignment, pressure in multilayer structures, and rheological and surface adhesion issues between the solid master and the imprinted resin in high aspect ratio structures. This is necessary to demonstrate production rates and quality control needed for competitive industrial fab production.



Fig. 15. A SFIL machine (courtesy Molecular Imprints Inc).

### **13. Carbon nanotube fiber fabrics and nanocomposites [21]**

Besides lower-cost mass production of carbon nanotubes, e.g. via hydrocarbon decomposition by liquid-phase self-regulated arc discharge, progress has been made towards fabrication of fibers out of water suspensions of polyvinyl alcohol (PVA) strands wrapped around carbon nanotube bundles. Key to this development is manufacturing of sufficiently long fibers by a gel drawing process through spinning pipe orifices assisting the fiber coalescence (R. Baughman et al). The resulting carbon nanotube reinforced fibers display toughness 4 times higher than spider silk and 17 times higher than Kevlar, stiffness twice as high and strength 20 times that of steel wire, which makes them suitable for impact-proof barrier fabrics. These are also electrically conductive and could power connected electronics, sensors and communication devices. Fibers in twisted pair arrangements also exhibit supercapacitor behavior for storage of electric charge in energy systems. In addition, carbon nanotubes are presently integrated with graphite fibers in nanocomposites for sporting goods such as tennis racquets, with high stiffness and custom shock absorption properties. The cost of the carbon nanotube manufacture is still the limiting factor for such applications.

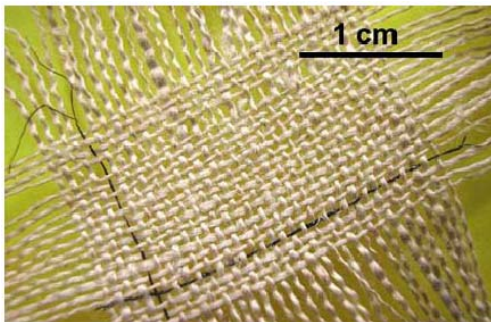


Fig. 16. Carbon nanotube fiber fabrics (courtesy UT Dallas)



Fig. 17. A carbon nanotube nanocomposite tennis racket (courtesy Babolat Inc.)

### **14. Nanocomposite dental filling materials [22]**

Besides nanopowder-laden chemical mechanical polishing (CMP) pads already on the market for wafer planarization in semiconductor manufacturing, polishing mechanisms are crucial in the present introduction of nanocomposite filler materials to the dental industry. Nanoparticles in filler composites minimize interference with the longer visible light wavelengths, thus creating aesthetically indistinguishable materials from natural tooth structure to the eye. At the same time the nanoscale particle size yields improved polishability, compared to microhybrid composites containing 0.4-0.6 micron sized particulates, while still maintaining excellent mechanical properties suitable for high stress-bearing restorations. Besides initial polish, superior polish retention (typical of microfills) results from the smaller crater and protrusion asperities generated by material wear in service, thus ensuring longer lasting luster of dental fillings.



Fig. 18. Comparison of a microhybrid and nanocomposite dental filling (courtesy of 3M-ESPE Filtek Supreme Universal Restorative)

### **15. Atomic Force Microscopes in Process Control [23]**

After the original introduction of scanning tunnelling microscopy (STM) in 1981 (Gerd and Binnig), Atomic Force Microscopy (AFM) has evolved to play a key role in the nanotechnology laboratory including biology, life and material sciences. Because it does not require ultra-high vacuum or cryogenic temperature environments, the AFM is also evolving into a practical quality control tool in the manufacturing industry, including nanocoatings, nanocomposites and the semiconductor industry. Sampled statistical process control (SPC) is in use by chip manufacturers to analyze the wafer surface for defects before the next step of the production process, using AFM surface profiling and leading in productivity improvement in semiconductor automation applications. Current research also focuses on defect management and repair using the nanomanipulation capabilities of the AFM.



Fig. 19. An AFM configuration (courtesy Veeco Metrology Group).

### **16. Silver nanocoating and nanoparticle sterilization [24]**

The well known disinfectant and antibiotic properties of electrolytic silver are being exploited in Ag<sup>+</sup> nanoparticle form, with large active surface area, for sterilization of heavily biologically

stained laundry loads from bacteria and mould in special washing machines. The inside of the power drum is covered with a silver particle-laden nanocoating with disinfection action, while the silver sterilization system of the machine generates and dispenses Ag nanoparticles to the laundry during the rinse cycle. A self-cleaning filtering function removes completely the particles from the tub after the end of the laundry. The silver sterilization washing machine was shown to kill 99.9% of bacteria without bringing the laundry to boil, therefore reducing energy and detergent requirements and contributing to environmental and health protection. This is initially targeted for clinical institutions, while commercial versions of the green appliance are in preparation.



Fig. 20. A silver sterilization washing machine (courtesy Samsung Electromechanics)

### **17. Fire retardant barrier nanocomposites [25]**

The introduction of nylon-matrix nanocomposites with montmorillonite clays (MMT) in late 1980s (Toyota Central Research) was followed by development of several specialty materials. In the original nanocomposite, MMT (a layered aluminosilicate clay) nanoflakes just 1nm thick were dispersed at <5% filler weight (compared to typical 30% of talc and glass reinforcements) in nylon 6 resin, greatly improving mechanical strength, heat resistance and dimensional stability as demonstrated in timing belt cover applications. Besides improved appearance and recyclability due to the smaller filler loadings, nanocomposites with clay fillers have improved gas barrier properties (over 3 times for oxygen, compared to unfilled nylon) making them appealing for packaging applications. In addition, since nano-dispersed MMT clays appear to be char-forming catalysts making non-char forming polymers, such as polystyrene, to form char, the nanocomposites display improved fire retardancy and flammability properties. Further research is under way in manufacturing aspects, such as MMT exfoliation during polymerization, melt processing or solvent dispersion during melt blending of the resin.

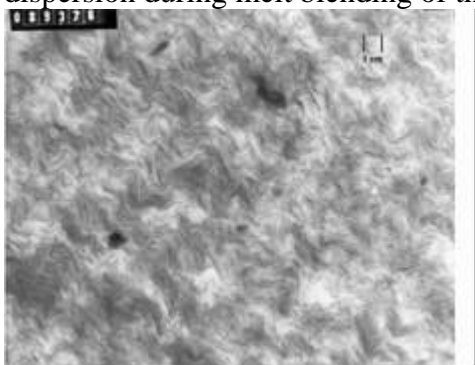


Fig. 21. Nylon-MMT nanocomposite (courtesy Southern Clay Products Inc.)

### **18. Mesoporous catalyst materials by liquid crystal templating [26]**

For mesoporous catalyst substrates with pores larger than 1.3 nm, zeolites and zeolite-like materials reach their stability limits. In 1992, the synthesis of a new class of mesoporous material (MCM-41) molecular sieves, was presented. MCM-41 are amorphous, hexagonally packed silicates and aluminosilicates with a uniform, honeycomb-like channel structure. The diameter of these channels can be adjusted between ~1.6 to 10 nm during synthesis, yielding surface areas reaching ~ 400 to more than 700 m<sup>2</sup>/g. Their production is achieved by self assembly of amphiphilic surfactants in

micelles as structure directing elements in a liquid crystal templating sol-gel process. The micelles are encapsulated by the inorganic material balancing the micelle charge, and the organic surfactant is finally removed by thermal calcination. Attempts to produce crystalline MCM-41 are under way.

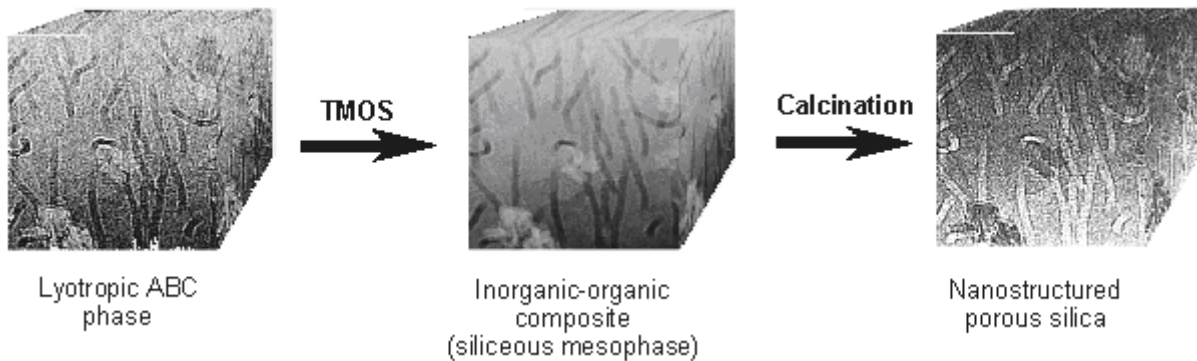


Fig. 22. MCM-41 fabrication and mesoporous structure (courtesy Mobil)

### 19. Nanomanipulator systems [27]

A fundamental requirement for both laboratory sample analysis and processing, as well as industrial fabrication of nanostructures requiring precision alignment and registration, is nanoscale positioning and orientation by a nanomanipulator system. Such 4 degree of freedom precision nanomanipulators, based on honeycomb drive or piezoelectric MEMS yielding positioning resolutions in 10s of nanometers and rotary resolutions down to 10 microrads, are commercially available, while full 6 degree of freedom systems are under way. These are under computer of haptic interface navigation, and compatible with standard electronic, optical or probe microscopes for sample manipulation. Other applications include nano-testing rigs for mechanical properties such as elastic modulus, resonant frequency and friction coefficient, as well as in nano-processing such as separation and joining of nanostructures.

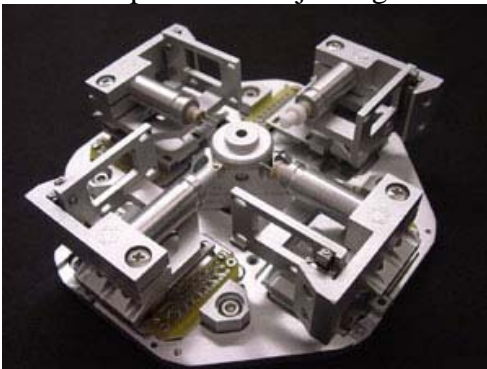


Fig. 23. A nanomanipulator system (courtesy Zyvex)

### 20. Pharmaceutical delivery vector production [28]

Nanoparticle vectors with physicochemical properties promising a biotherapeutic action, such as colloidal gold, are currently manufactured for targeted delivery of biomolecules and drugs to selected cells or molecular cell structures. In colloidal gold, for example, the Au nanoparticles can acts as docking sites for more than one biomolecular species, thus yielding targeted delivery of pharmaceuticals. This is now exploited for non-toxic delivery of cytokines, such as tumor necrosis factor (TNF), for immunotherapeutic treatment of cancer cells. There is also promise for selective gene delivery of DNA genetic material to the interior of specific cells.

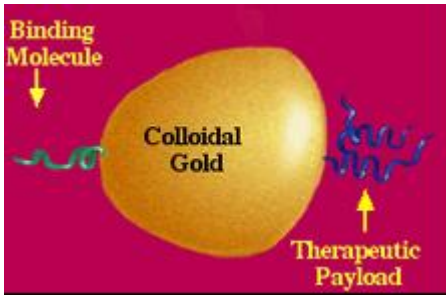


Fig. 24. Colloidal gold nanoparticle as a drug delivery vector (courtesy of CytImmune)

### 21. Liposome nanocapsules in cosmetic lotions [29]

Since the 1970's, the cosmetics industry have been producing liposome lotions for delivery of active ingredients to the skin strata. These are nanocapsules ranging between 130 and 600 nm, consisting of a tiny polymeric shell filled with fluid ingredients such as vitamin A, retinol and B-carotene, to effectively deliver their anti-aging and nutrition properties to the deeper skin layers. Recently the shell was coated with biodegradable polymer that is consumed by natural enzymes at the surface of the nanocapsules, thus releasing the active ingredients in the lower strata of the skin. In addition, lotion nanoparticles are ground under high pressure to 50-60 nm, yielding a translucent product suggesting purity and cleanliness.



Fig. 25. Nanocapsule shell structure in lotion (courtesy L'Oreal).

### 22. Nanocoated self-cleaning glass [30]

The self-cleaning glass features a coating film with photocatalytic and hydrophilic properties. The durable and transparent coating consists of nanostructured titanium dioxide ( $\text{TiO}_2$ ) which is integrated with the hot glass during its manufacturing formation process into a long-lasting product. The photocatalytic properties of the coating are activated by UV illumination and gradually disintegrate and loosen organic dirt deposited on the glass. The hydrophilic properties reduce surface tension and lead to sheeting rather than beading of water on the glass, which helps flushing the surface clean and accelerating drying, leaving the glass with minimal spotting and streaking mostly from inorganic residues. Self-cleaning glass is manufactured in standard and energy-saving low-W panels for windows etc.



Fig. 26. Photocatalytic and hydrophilic processes in self-cleaning of glass (courtesy PPG).

### 23. Drug and gene sequencing arrays [31]

Development and production of new nanostructured pharmaceuticals and biosensor nanodevices has been greatly accelerated by electronic sequencing microarrays, capable of rapid identification and precise analysis of biomolecules including DNA and RNA. Because of their natural electrical charging, the molecules are rapidly moved and concentrated in addressable designated sites of the

chip. Such microarray nanochips are available for on-chip non-PCR amplification, e.g. through strand displacement methods enabling exponential amplification of DNA by an isothermal reaction, simplifying detection at low levels of the diagnostic target. They are also available in fluorescent kinase assay platforms for electronic screening applications for drug discovery of kinases, phosphatases and proteases, with several hundred well microtiter plates, without use of antibodies or radioactivity. These enable disease diagnostics, drug discovery, novel oligonucleotide chemistries, as well as forensic applications via genetic-based in-vitro human detection and biowarfare agent detection.

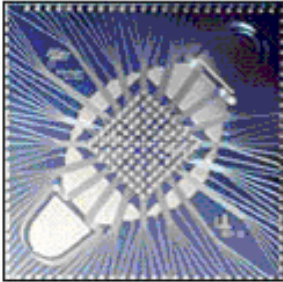


Fig. 27. A nanochip electronic microarray (courtesy of Nanogen).

#### **24. Nonvolatile Random Access Memory [32].**

Nonvolatile random access memory (NRAM™) is developed, as a form of memory that can replace flash memory, dynamic RAM (DRAM), static RAM (SRAM), and ultimately hard disk storage. NRAM™, has the following characteristics: permanently nonvolatile like flash, faster than DRAM, smaller cell size than DRAM, lower power consumption than DRAM, as portable as flash memory, unlimited read/write cycles unlike flash, and highly resistant to environmental forces (heat, cold, magnetism, alpha particles, radiation). Carbon nanotubes have a combination of properties that make them highly valuable for use in electronics applications: higher electrical conductivity than copper or gold, higher thermal conductivity than diamond, higher tensile strength than steel, and of course a very small size (diameter of 1.4nm, wall thickness of one atom). However, there are substantial barriers to using them in a mass production process—their properties are hard to control, they cannot be easily positioned, placed or aligned, and they are generally available only with substantial particulates and contaminants included. Solutions are developed which allow carbon nanotubes to be used in a production CMOS process in any existing semiconductor fab.

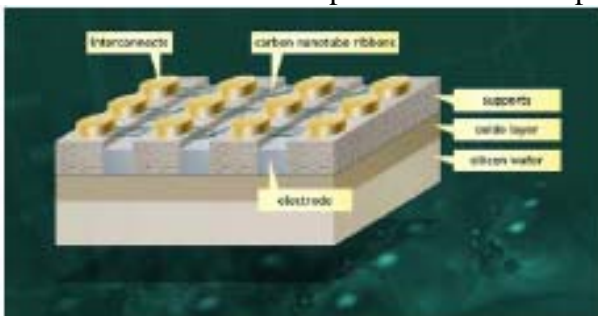


Fig. 28. Platform for nanoelectronics using carbon nanotubes (schematic of the NRAM Design, Courtesy Nantero)

#### Key advances

The previous advances in nanomanufacturing production bear a number of enabling and/or disruptive technological achievements in common, including [33]:

***-Creating a variety of primary and intermediary standard components in the laboratory.***

Building block raw materials and intermediate structural elements have been made available recently, at quantities and qualities mostly for laboratory research, but usually not for industrial manufacturing. These include 0-dimensional quantum dots on surfaces and buckyball fullerenes; 1-dimensional carbon nanotubes, polymer and ceramic nanofibers, nanowires and nanorods; 2-dimensional ultrathin film patches and exfoliated clays; 3-dimensional ceramic nanopowders, polymer dendrimers and complex organic molecules and biomolecules such as proteins and DNA; and composite structures such as templated block copolymer and carbon nanotube arrays. See case studies 1, 2, 3, 16, 17, 20, 21 etc. above.

#### ***-Creating heterogeneous nanosystems***

These include multidimensional nanostructures made of dissimilar materials or components, such as multi-layered ferromagnetic/dilute paramagnetic semiconductor structures in spintronics, semiconductor/organic monolayer structures in molecular electronics, templated biomolecule scaffolds on semiconductor substrates, and nanoparticulate dispersions or oriented nanotube /nanofiber reinforcements in nanocomposites. Progress has been also made in understanding the properties of heterojunction interface surfaces as related to their fabrication. See case studies 4, 5, 13, 14, 17, 18, 22 etc. above.

#### ***-Patterning and templating***

Geometrical shaping and structuring processes at the nanoscale are at the heart of manufacturing technologies for production of functional devices and integrated multi-element systems. Several two-dimensional, parallel mask-based hard lithography methods such as extreme UV and X-ray (LIGA) are combined with serial scanning beam-based ones such as molecular beam epitaxy, electron and focused ion beam, or probe-based methods including AFM, STM, two-photon, near-field optical and mechanical tip scribing, as well as parallel soft lithography based on contact nano-imprinting, molding, embossing etc. These are also extended to 3-dimensional patterning by stereolithographic layering, electrostatic/magnetic/ fluidic directional growth and extrusion processes, templating by lithographically induced self assembly etc. Assistive material transfer technologies include plasma/laser vaporization, electrophoretic and laser-guided transport, as well as thermal spraying, cladding and sintering. See case studies 6, 7, 8, 9, 10, 11, 12, 15, 23, 24 etc. above.

#### ***-Interconnect design and development***

Research on multi-chip modules and MEMS has shown that major challenges for achieving nanometer scale products will be the ability to communicate with the microscale and macroscale world. Nanoscale interconnects that are reliable, cost effective, and have the capability to link structures of diverse types, materials, and sizes are required. See case studies 7, 8, 13, 23, 24 etc. above.

#### ***-Manufacturing “by design”***

The interdependence between product design and manufacturing process and the requisite holistic approach adopted at larger fabrication scales is even more evidently realized in nanomanufacturing, because of the peculiarity of the matter-process interaction mechanisms at the nanoscale. The geometrical and material design of nanodevices is adapted to the structuring capabilities of the new nanomanufacturing technologies; and inversely, sequences of multiple diversified process step protocols are developed for implementation of custom-designed structures. See case studies 2, 3, 5, 13, 14, 16, 17, 18, 21, 22 etc. above.

#### ***-Manufacturing scalability.***

The transition from fundamental analysis and understanding of nanoscale phenomena (nanoscience) and synthesis or fabrication of engineered structures in the laboratory (nanotechnology), to high-rate, high-quality production of integrated systems in industry (nanomanufacturing), is presently an emerging field. Recent advances can be attributable to progress in building the necessary raw materials and building blocks, in integration processes of dissimilar elements, in geometric shaping of multi-dimensional structures, in connecting the process conditions to the resulting product features, and in hardware instrumentation and simulation software for construction and characterization at the nanoscale. An example is chemical-mechanical polishing (CMP – R. Singh, MRS 2002). See case studies 4, 5, 10, 13, 14, 16, 21, 22 etc. above.

***-Advanced instrumentation and simulation for analysis.***

Analytical equipment hardware for laboratory experimentation, besides off-line scanning probe and spectroscopic microscopy instruments for characterization of nanomanufactured structures, is presently extended to in-process metrology techniques, including near-field interferometry and nano-pattern encoding, and real-time imaging methods such as concurrent FIB process/SEM imaging etc. In addition, computational software such as multi-scale molecular dynamics simulations, typically applied for structure-property in-service analysis, is becoming available for process-structure studies during manufacturing processing. See case studies 9, 10, 11, 12, 13, 15, 19, 23 etc. above.

***-Validated models of manufacturing processes and equipment.***

The distinction between manufacturing process performance and product performance is blurred and interwoven when considering nanoscale products. This requires one to view first part correct methods (in this case many million, billion) to be an absolute. Following the path of today's precision machining industry, nanometer-scale manufacturing equipment manufacturers must demonstrate to their customers the performance capabilities of their equipment with assigned uncertainties. This will require rigorous performance measures that are traceable to fundamental standards. See case studies 1, 3, 9, 11, 12, 15, 24 etc.

**Future Research Directions and Needs**

Nanotechnology will fundamentally change the way both basic types of manufacturing – continuous and discrete – are conducted in the future. Continuous manufacturing refers to the production of bulk substances or materials, e.g., chemicals or rolls of sheet metal. Discrete manufacturing is the production of individual parts, e.g., bolts or devices such as integrated circuits or assembled systems such as computers. Atoms, molecules and clusters are the “raw material” for manufacturing at the nanoscale. As a result the processes and equipment for manufacturing at the nanoscale are expected to be significantly different from even those currently used for microfabrication in the size range over 100 nm. The special research opportunities include [34, 35]:

**a. Material development**

- Basic understanding and modeling of phenomena and processes leading to synthesis, manipulation and monitoring of matter at the nanoscale necessary for developing new manufacturing techniques. Unlike bulk systems, manufacturing at the nanoscale would require deep understanding and simulation methods of processes. This includes controlled nucleation into nanocrystals, passivation, self-assembling, and manipulation for inclusion into larger structures.
- Methods to characterize, monitor, screen, separate and control the size / shape / polydispersity and surface or volume features of nanostructure building blocks.

**b. Material manipulation and control for creating nanosystems**

- Positioning, orientation, dispersion, clustering and directed self-assembling of molecules, macromolecules, nanoparticles and other nanosized components. Non-covalent bonds and information contents are essential. Precise and efficient manufacturing using self-assembling is a primary goal. Another goal is increasing the speed of self-assembling, using external fields and catalysts.
  - Synthesis and fabrication methods for the nanostructure building blocks in the 1-100 nanometer range with tailored properties and functions from a wide range of materials. (Such structures include quantum dots (0-D), tubes, wires (1-D), surfaces (2-D), clusters and other three-dimensional molecular assemblies)
  - Packaging and transportation of nanomaterials and building blocks, such as transfer by ultrasonics and fluidized beds-nanofluidics. The objective is to present the nanomaterial and building blocks into the manufacturing process in a desired orientation, position, time, and sequence.
  - Directed, hierarchical self-assembly of building blocks into functional devices and systems. This includes bio-inspired processes that mimic intra-cellular structuring functions and other biological systems (biomimetic manufacturing).
- c. Scale-up and integration with micro and macro systems**
- Integration of bottom-up and top-down fabrication techniques into the most cost effective and optimal throughput manufacturing.
  - Scale-up, parallelization and integration capability of manufacturing techniques, such as parallel probe or beam arrays and fab-on-a-chip approaches.
- d. Tools for manufacturing**
- Modification and control of the building block surface composition/structure to ensure stability and functionalization to enable subsequent directed assembly. Technologies for characterization and processing of non-conducting, compliant surfaces such as those of organic, biological and other soft components. Development of sustainable, user- and environmentally-friendly, affordable, high-throughput patterning technologies.
  - Developing and applying replication methods for nanostructures
  - Introduction of models and control methods, including analytical capability for real-time processing feedback and quality control. Developing equipment and processes to achieve directed molecular assembling into functional nanostructures and devices, including highly parallel processing and robotics.
  - Manipulation and/or locomotion of building blocks and nano-robots for localized assembly, repair or decontamination on two-dimensional surfaces.
  - Developing of versatile assembling and separation processes for nanostructures, and controlled-geometry material deposition and ablation (nanoscale SFF)
  - Techniques for the cost effective removal / repair / trimming of nanofabricated structures and properties.
- e. Tools for measurement and standards**
- Technologies for chemical and structural characterization of nanoparticles and building blocks (besides their geometrical characterization).
  - Taxonomy and standardization of structural and functional properties of the building blocks, and coding into information databases for use in their integration for manufacturing processes. A key objective would be to capture and represent semantic level information enabling improved interoperability and information-knowledge exchange.

- Measurement, understanding and control of the role of surface / interface properties in nanocomposite processing and properties. Developing three-dimensional processing and non-destructive subsurface monitoring technologies.
- Integration of in-process sensing and monitoring technologies with the manufacturing methods.
- Accounting for the broad complexity of problems involved in the production of systems containing structure and function across many length scales, and hierarchical multi-scale processing and sensing technologies.
- Telefabrication and telecharacterization –capable equipment and instrumentation.
- Nanoscale sensing and actuation technologies and tools, and special real-time control algorithms appropriate to the particular resolution and bandwidth requirements of nanomanufacturing processes, for their closed-loop, ex- or in-situ control.

**f. Model development**

- Tools for modeling and simulation of the broad range of manufacturing processes involving nanostructures, so that the processes may be understood, optimized, and designed.

**h. Safety**

- Understanding, modeling and control of the health, safety and environmental impact aspects of nanoparticle processing and nanomanufacturing technologies, as well as those during nanomanufactured product service including larger-scale manufacturing processes with nanostructured materials and tools (CMP, nanocoated tool machining etc).

*Scientific and technological research needs*

To implement the vision in nanomanufacturing, there is a clear need to complement existing predominantly scientific and prototyping facilities for nanoscale research, with the respective engineering and manufacturing infrastructure [36]. This will allow completion of a powerful armory of resources to address synthesis and scale-up of nanoscale materials and structures into functional devices, integrated systems and interconnected architectures, leading eventually to useful products and services at our physically relevant scales. Much like in the human organism, where nanoscale structures of molecular organelles in the cell nucleus are functionally integrated into microscale assemblies at the cell level, and further into the variety of mesoscale tissues and eventually into the diversified macroscale organs of the body, it is expected that engineered nanostructures and functions will provide the building blocks for fabrication across dimensional scales. To provide the required multi-functionality, such technologies will naturally need to encompass and transcend the entire spectrum of energetic or disciplinary domains, including their mechanical, fluidic, electrical, magnetic, optical, chemical, biological etc. aspects. However, the fundamental manufacturing research issues of producibility, predictability and productivity of such technologies must also be factored and implanted into this endeavor, in order to harvest industrially viable and broadly useful outcomes from such an investment in nanomanufacturing infrastructure. Some of the key features of the necessary resources include [37]:

- Geographically distributed nanomanufacturing research and nanofabrication user facilities, including adequate characterization capabilities, are needed for both vertical functionality research/development and education/training of the workforce.
- Efficient networking of new nanomanufacturing facilities to the existing nanoscience and nanotechnology center infrastructure, and capability for teleoperated remote manufacturing (telefabrication, telecharacterization) for wider accessibility.

- Infrastructure for development of measurement and manufacturing tools and standards.
- Models and simulation software for nanomaterials processing, with the required attention to boundary conditions, such as in nanofluidics. Involvement activities and opportunities at nanomanufacturing facilities for health, environmental, social and economic scientists, underrepresented groups, and foreign visiting scholars for promotion of international pre-competitive research and education collaborations. Support international challenges and national priorities such as research in nanotechnology tools for security. Support for small business incubation and growth, to accelerate manufacturing technology transfer to industry. Marketplace-neutral resources to facilitate people, software, and science-based understanding integration across the entire manufacturing enterprise.
- Appropriate incentives to promote sharing of facilities, staff time, and other resources.
- Use and creative adjustment of the existing infrastructure at universities, government laboratories and industry.

Following a systems approach in nanomanufacturing, there is an identified need to systematize and link new nanomanufacturing infrastructure with the existing resources into a comprehensive and coherent network. This nanomanufacturing infrastructure can capitalize on cyber-networking and communication structures, to provide a hierarchical system architecture with functionality and utilization larger than that of the sum of its components. This can consist of properly connected virtual centers and sub-networks, optimizing physical accessibility of the resources to all geographic areas of the country, and promoting their broader use via teleoperation (telecharacterization and telefabrication of nanostructures) over the network. For the purpose of maximizing their utility, it is important that this investment in nanomanufacturing infrastructure be shared and co-funded as much as possible by governments, academic institutions and industrial organizations, encouraging their members to take advantage of the joint resources.

Beyond enabling and shaping new research directions in nanomanufacturing, this infrastructure can be the cradle of new educational and training programs in science and engineering, as well as the heart of public information and participation activities, reaching out to the broader society. It is recognized that education of human resources in this nascent field of knowledge, including teaching and mentoring of future nano-science and engineering researchers and educators, and training of professional workforce for the emerging nanotechnology industry, is at least as important as the infrastructure facilities [38,39]. These resources will provide the platform for establishing new educational programs in nanomanufacturing, from interdisciplinary college majors and disciplinary minors to graduate degrees, post-doctoral programs and continuing education certificates, to high-school summer courses and curriculum throughout the pre-college education. Training courses and seminars for practicing professionals and industry personnel will also utilize these facilities, either by hands-on projects and demonstrations, or by tele-operation via the internet. The networked resources will attract involvement of researchers in larger dimensional scale topics and instructors of multiple related themes, as well as non-traditional contributors to nanotechnology, such as behavioral, economic and social scientists [40,41]. At the same time, the infrastructure will be open to the public for laboratory visits and virtual demonstrations on the web, and sponsor special nanotechnology awareness events and activities to promote public understanding of the new technologies, their new opportunities for education and employment, and their impending impacts to society.

### International Strategies

In the international arena [42,43], the European Commission through its latest Framework Programme 6 [44] set examples in infrastructure networking through creation of virtual centers.

These unite university and industry resources and alleviate the need for new buildings and staff for research programs. Europe also promotes access and utilization of large infrastructure by requiring the member states to pay annual dues for these facilities. The national governments therefore have incentives to strongly encourage their researchers to work with them, in expectation of the best possible outcome for their investment [45]. On the other hand, the government in Japan, according to a recent WTEC report in MEMS technologies, funds directly mostly infrastructure, as opposed to individual research projects of faculty. Japan has extensive facilities for specialty part building from a variety of materials, not just by traditional Si-based lithography for integrated circuits, and it leads in manufacturing of microscale devices by assembly. In the USA, over the past few years, the federal government has spearheaded support of nanotechnology facilities through the National Nanotechnology Initiative (NNI) [46], which united the federal agencies in a coordinated and complementary development plan. Many individual states, such as California, Florida, Illinois, New York, Pennsylvania and Texas have also followed this example by generously committing resources to nanotechnology. Larger industries such as Lucent Technologies are presently availing their research facilities in nanotechnology to academia.

#### Case Study – The National Science Foundation in the USA

The National Science Foundation (NSF) in Arlington, Virginia is the leading federal agency in the USA in administering the NNI program through the federal Nanoscale Science, Engineering and Technology (NSET) committee. In nanomanufacturing, in 2001 NSF has established a new Nanomanufacturing Program, which focuses on fundamental research for manufacturing processes, new theoretical models/simulations, and instrumentation for characterization/quality control. Since 2001, all NSF Directorates have joined forces in an annual Nanoscale Science and Engineering solicitation (NSE). In its first year, the NSE provided for the establishment of six Nanoscale Science and Engineering Centers (NSEC) at Columbia (electronic transport in molecular nanostructures), Cornell (nanoscale systems in information technologies), Harvard (nanoscale systems for device applications), Northwestern (integrated micropatterning and detection technologies), Rensselaer (directed assembly of nanostructures) and Rice (biological and environmental engineering). The NSECs will provide mostly a science base for the implementation of nanotechnology [47]. To complement such developments in nanoscience with nanotechnology research, the NSE for FY 2002 included a new topic in Manufacturing at the Nanoscale.

Over the last decade, NSF has taken steps in establishing the required facilities with special initiatives since 1991, including those in Nanoscale Instrumentation (1995, \$2M), Partnerships in Nanotechnology (1998, \$13M), and Nanoscale Modeling and Simulation (2000, \$10M). Several Material Science and Engineering Research Centers, Science and Technology Centers, Industry-University Cooperative Research Centers and Engineering Research Centers in related themes have provided nuclei of nanoscale resources across the country. In particular, the National Nanofabrication Users Network (NNUN) was established in 1994 and its funding was renewed in 1999 by four NSF directorates (ENG, MPS, BIO and CISE). The NNUN has five centers at Cornell, Howard, Penn State, Stanford and the UC-Santa Barbara, to provide the nation's researchers with access to advanced nanofabrication equipment and expertise, and expand applications of nanotechnology. These centers currently boast over \$90M worth of modern equipment, with particular strengths in 2-D lithography, thin film deposition, surface processing and characterization technologies. Examples of currently funded NSF centers contributing to manufacturing at the nanoscale are:

#### Nanoscale Science and Engineering Centers (NSEC) in Manufacturing:

- Scalable and Integrated Nano-Manufacturing (SINAM, UCLA)

- Nanoscale Chemical, Electrical, Mechanical and Manufacturing Systems (Nano-CEMMS, Univ. of Illinois at Urbana-Champaign)
- Center for Affordable Nanoengineering of Polymer Biomedical Devices (CANPBD, Ohio State University)
- New England Nanomanufacturing Center for Enabling Tools (NENCET, Northeastern Univ, Univ. of Massachusetts Lowell and Univ. of New Hampshire)
- Center for Integrated Nanomechanical Systems (Univ. of California Berkeley)

Engineering Research Centers (ERC):

- NSF/SRC Center for Environmentally Benign Semiconductor Manufacturing (Univ. of Arizona)
- Center for Particle Science and Technology (Univ. of Florida)

Industry University Cooperative Research Centers (IUCRC):

- Center for Precision Metrology (CPM, Univ. of North Carolina Charlotte)
- Center for Lasers and Plasmas for Advanced Manufacturing (LAM, Old Dominion Univ.)
- Center for Advanced Studies in Novel Surfactants (Columbia Univ.)
- Ceramic and Composite Materials Center (CCMC, Univ. of New Mexico and Rutgers Univ.)
- Center for Advanced Polymer and Composite Engineering (CAPCE, Ohio State Univ.)
- Cooperative Research Center in Coatings (Univ. of Southern Mississippi and Eastern Michigan Univ.)
- Particulate Materials Center (Penn State Univ.)
- Center for Biocatalysis and Bioprocessing of Macromolecules (CBBM, Polytechnic Univ. NY)

Materials Research Science and Engineering Centers (MRSEC):

- Center for Quantum and Spin Phenomena in Nanomagnetic Structures (Univ. of Nebraska)
- Center for Nanoscale Science (Penn State Univ.)
- Center for Materials for Information (Univ. of Alabama)
- Materials Research Science and Engineering Center (Univ. of Chicago)
- Center for Chemical Assembly of Thin Films Using Nanoparticles (Columbia Univ.)
- Materials Research Science and Engineering Center (MIT)
- Center on Polymer Interfaces and Macromolecular Assembly (Stanford Univ.)

Science and Technology Centers (STC):

- Center for Embedded Networked Sensing (CENS, UCLA)
- Nanobiotechnology Center (Cornell Univ.)

There are current plans for integrating these facilities into a complete, comprehensive and versatile nanomanufacturing infrastructure network [47]. This will complement the existing centers with new nodes focusing on nanomanufacturing building blocks, coatings and surfaces, consolidates and composites, biochemical dispersions and structures, processing and integration, system architectures, modeling tools and instruments, electronic/magnetic systems, photonics and optics, biodevices and systems, and environmental, energy, health and safety systems. The necessity for such nanomanufacturing facilities was suggested by the research community in a number of workshops with participation of the federal agencies, small businesses and the European Commission, in order to support evolving needs for discovery, innovation and applications of nanotechnology. The new facilities will feature new instrumentation and machinery with emphasis

in 3D manufacturing, scale-up integration, measurement and metrology, and modeling and control of both top-down and bottom-up manufacturing technologies. The networked facilities must be designed to broaden participation of academe, industry and federal laboratories by geographical distribution and cyberspace tele-operation of the equipment. This infrastructure is intended to foster interdisciplinary research, with education and training of the workforce integrated at all levels, and with opportunities for engaging the social sciences and addressing the societal impacts of nanomanufacturing.

### **Concluding Remarks**

Manufacturing of nanostructures, devices and systems will be realized with a high degree of process control in sensing and actuation of matter at the nanoscale. This is necessary to achieve prescribed performances in production and service, and with hierarchical integration across dimensional scales to incorporate nanostructures into microscale architectures and macroscale products. It may combine bottom-up, directed molecular or particulate assembling techniques with top-down, high-resolution and speed macroscopic fabrication techniques. Highly efficient manufacturing processes are envisioned, minimizing materials, energy, waste and environmental impact- and enabling high-rate, cost-effective, repeatable production suitable for industrial implementation. These will make possible the fabrication of new products and offering of new services, thus enabling beneficial impacts of nanotechnology to the economy and society.

The role of nanoscale manufacturing is:

- to enable new technologies, products and services that are not possible otherwise.
- to address issues of general public interest such as increase in work efficiency, healthcare technology, occupational health and safety, the protection and improvement of the environment.
- to support traditional industry with new enabling technologies and to establish new non-traditional manufacturing ventures and markets
- to rekindle economic development and growth, and to offer new employment opportunities, broadening participation and geographic distribution of activities and resources
- to establish international cooperation in modern and advanced manufacturing.

As with groundbreaking developments in semiconductor electronics, oncological diagnostics, biotechnology and information technology in the past, there is a necessity to develop the proper nanoscale manufacturing infrastructure base so as to make the research laboratories the birthplace of such discoveries in manufacturing technologies. There is an urgent need to develop an integrated network taking advantage of the university system, to attract and educate the future breed of nanoscale manufacturing scientists and engineers, and to train the new professional workforce needed in nanotechnology industries all over the world.

Beyond this research and education enterprises, the investment in nanoscale manufacturing infrastructure aims to generate completely new industry sectors, in manufacturing of a multitude of nanoscale devices and products, and in offering associated services in their design, fabrication, integration and use. This offers the opportunity to create value added in high-technology manufacturing, similar to that developed e.g. by the traditional automotive industry in the previous century. An advanced nanomanufacturing infrastructure network would attract discoveries and ideas all around the world for analysis, implementation and eventual benefit to the international economy and society. Nanomanufacturing promises to open up new markets and revitalize the global economy. At the same time a selective, geographically distributed investment in nanomanufacturing infrastructure can offer a well balanced technical and economic development, and therefore broaden its benefits to all areas, and promote participation of diverse groups of its

population. Such infrastructure will therefore provide a critical link in delivering the promise of nanotechnology, "...to change the way almost everything – from vaccines to computers to automobile tires to objects not yet imagined – is designed and made" [46].

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