The Center for High-rate Nanomanufacturing

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Scientific breakthroughs in nano-science have come at a surprisingly rapid rate over the past few years. The transfer of nano-science accomplishments into technology, however, is severely hindered by a lack of understanding of barriers to nanoscale manufacturing. For example, while shrinking dimensions hold the promise of dramatic increases in data storage densities, realistic commercial products cannot be realized without first answering the question of how one can wire billions of nano-scale devices together, or how one can prevent failures and avoid defects. To ensure that discoveries lead to commercially viable products in a time-span faster than the traditional linear 20-30 year window[1,2], it is important to address the nanomanufacturing fundamental scientific barriers in parallel with the ongoing nanoscience research.

The NNI Grand Challenges and the NSF Workshop on Three Dimensional Nanomanufacturing held in Birmingham, Alabama, in January 2003 (www.nano.neu.edu/nsf_workshop.html) identified three critical barriers to nanomanufacturing:

- How can we control the assembly of 3D heterogeneous systems, including the alignment, registration, and interconnection at three dimensions and with multiple functionalities?
- How can we handle and process of nanoscale structures in a high-rate/high-volume manner, without compromising the beneficial nanoscale properties?
- How can we test the long-term reliability of nano components, and detect, remove, or prevent defects and contamination?

The Center for High-rate Nanomanufacturing (CHN) has research thrust areas targeted to overcome these fundamental barriers.

Our Vision: Nanomanufacturing Through High-rate/High-volume Guided Self-assembly of Nanoelements

The Center's proposed novel tools and processes will enable high-rate/high-volume bottom-up, precise, parallel assembly of nanoelements (such as carbon nanotubes, nanorods, and proteins) and polymer nanostructures. Current nanotechnology research focuses on surface modification, matching molecules and "sockets" at the level of manipulating several to several hundred particles or molecules to be assembled into desirable configurations. Commercial scale-up and the promised economic windfall, however, will not be realized unless one can perform high-rate/high-volume assembly of nanoelements economically and using environmentally benign processes. Our proposed nanotemplates and processes will accelerate the creation of highly anticipated commercial products and will enable the creation of an entirely new generation of applications yet to be imagined, because they are developed

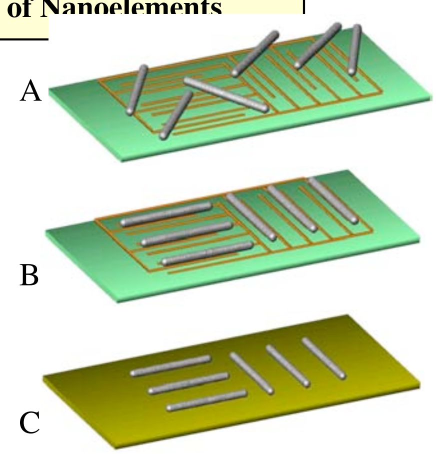

Fig. 1. Nanotubes deposited (A), assembled (B) on a nanotemplate, then transferred to a second substrates (C).

[1] For example, some MEMS applications, such as pressure sensors, started in the 1960's, took 30 years to reach full commercialization (accelerometers and other applications took 20 years)
[2] R. Grace, "Commercialization Issues of MEMS/MST/Micromachines: An Updated Industry Report Card on the Barriers to Commercialization", Sensors Expo Spring Proceedings, San Jose, CA, May, 2002.

with scalability and integration as a requirement. This includes understanding what is essential for a rapid multi-step or reel-to-reel process, as well as for accelerated-life testing of nanoelements and defect-tolerance. This Center will contribute a fundamental understanding of the interfacial behavior and forces required to assemble, detach, and transfer nanoelements, required for guided self-assembly at high rates and over large areas.

This Center introduces novel science to enable high-rate/high-volume nanomanufacturing. For example, the proposed high-volume room-temperature synthesis of uniform carbon nanotubes with precise dimensions and tunable properties presents an innovative approach in making carbon nanotubes. The bottom-up formation of fullerene nanowires via the supramolecular self-assembly of functionalized fullerenes will permit patterned nanofeatures with unprecedented resolution (< 2 nm separation). In addition, our new methods using nanotemplates for patterning polymer blends at high rates represent a unique approach that makes the process especially suitable for commercialization.

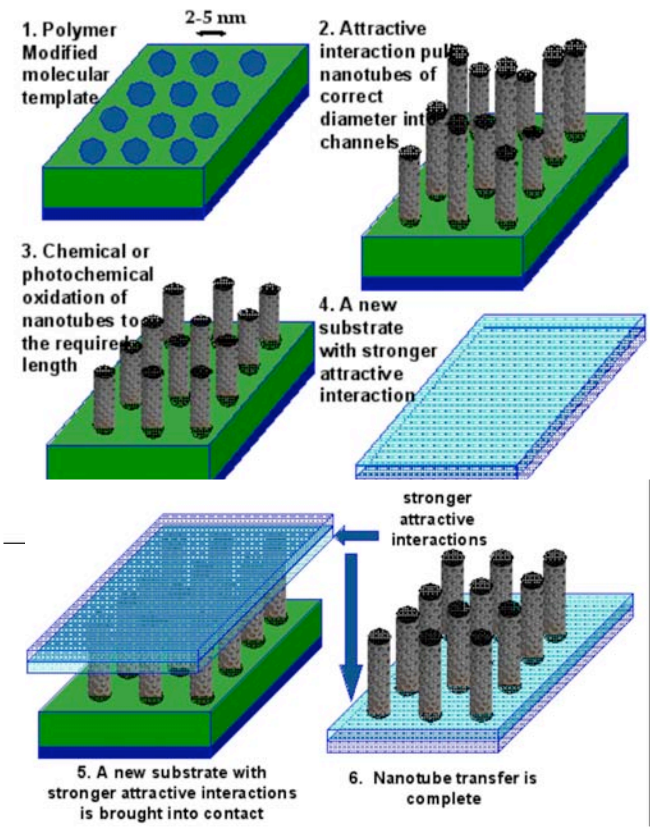

Fig. 2. Steps of 3-D molecular assembly.

Figure 1 shows the concept of the nanotemplate process. A 3-D nanotemplate (patent pending[3]) will not only enable the assembly of nanoelements in three-dimensions, but also their sorting and transfer to another substrate in a predetermined pattern. In Figure 2, the nanotemplate contains channels of uniform, but controllable size, spacing, depth and binding characteristics. This allows nanoelements of varying types (e.g., CNTs, inorganic nanotubes, etc.) to be non-covalently attracted into the channels of nanotemplates, perpendicular to the plane of the substrate surface.

Figure 3 illustrates how our team will create and apply the nanotemplates in high-rate/high-volume manufacturing using the two testbed prototypes in partnership with our industrial partners.

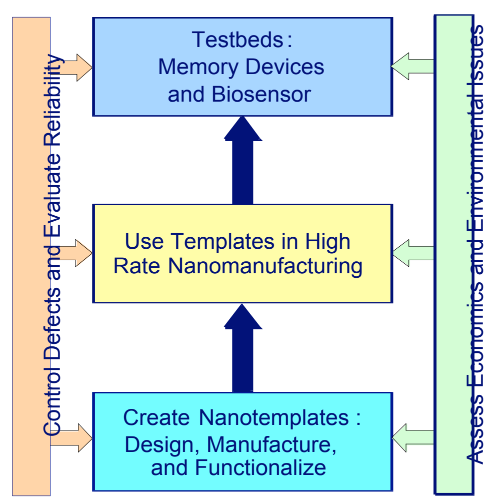

Fig. 3. The path to nanomanufacturing.

The Center for High-rate Nanomanufacturing will:

- **Create versatile nanotemplates**
    - Create uniform and nonuniform patterns from self-assembled fullerene nanowires, self-ordering growth of nanoarrays, and nanolithography
    - Develop functionalization methods to enable assembly of a wide variety of nanoelements

[3] A. A. Busnaina and G. P. Miller, "Precise Massive Selection and Parallel Three-dimensional Assembly of Carbon Nanotubes and Nanoelements" Pending US patent.

- **Employ nanoelements to enable high-rate/high-volume manufacturing**
  - Attain nanoscale self registration
  - Use the nanotemplates to sort and self-assemble nanoelements
  - Use the nanotemplates to guide the self-assembly of polymer melts
  - Synthesis of SWNTs with the desired size, functionality, and solubility for high-volume assembly
- **Manufacture two prototype testbeds**
  - Nonvolatile high-density memory device
  - High-sensitivity biosensor
- **Concurrently develop tools and methods to ensure long-term reliability**
  - Create novel reliability and characterization tools for nanoelements and connections
  - Develop nanoscale contamination control
  - Design defect and fault-tolerance systems
- **Concurrently assess the environmental, economic, regulatory, and ethical impacts of nanomanufacturing.**

CHN members include engineers, chemists, and physicists with strong expertise in both nanoscience and manufacturing. The strengths of the Center are based on the integration of the three core universities, with cross-disciplinary technical expertise, industry connections, and educational and outreach infrastructure. Moreover, many of the lead team members, including the PIs, have extensive manufacturing experience in addressing the challenging questions that will arise during the research. This core team will be supported by 13 companies that have committed more than $9 million dollars for the first five years to make the prototype testbed for proof of concepts and to transition the promise of nanotechnology to realistic and improved commercial products.

The efficacy of the nanotemplates and processes will be demonstrated by developing two products; a nonvolatile nanotubes memory device and a biosensor. The proposed single wall carbon nanotube memory device constitutes a non volatile memory with orders of magnitude higher density than silicon chips (the concept is shown in Figure 4). These nanotubes work in the cross bar architecture as nanoscale molecular switch devices[4]. The proposed testbed chip will be made and assembled using nanotemplates, in collaboration with Nantero. Nantero will use the developed nanotemplates with CMOS in a "hybrid" commercial testbed to reach ultimate scaling.

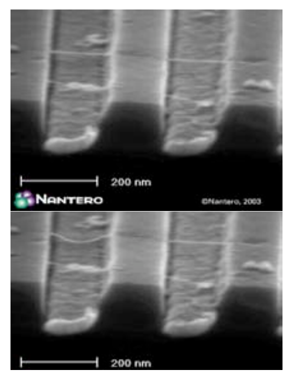

Fig. 4. SWNT switch.

The Center for High-rate Nanomanufacturing will leverage current and future efforts in nanoscience and technology by bridging the gap between scientific research and the creation of commercial products by established and emerging industries, such as electronic, medical, and automotive. Long-standing ties with industry will also facilitate technology transfer. The Center will build on an already existing network of partnerships among industry, universities, and K-12 teachers and students to deliver the much-needed education in nanomanufacturing, including its environmental, economic, and societal implications, to the current and emerging workforce. Finally, the partnership between CHN and the Museum of Science (Boston) will develop programs designed to increase public awareness of the critical importance of technology, specifically nanotechnology, to society. The academic partners in CHN will integrate their research into a comprehensive program of education programs to provide hands-on, team-based learning for the students in their institutions and for students and teachers in K-12 in their respective regions, and industry.

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[4] Y. Chen and R. S. Williams: "Nanoscale Patterning for the Formation of Extensive Wires," U. S. Patent 6,407,443; issued on June 18, 2002.