The United States has led the world in manufacturing for over a century. However, the nation’s trade balance in advanced technology manufactured products shifted from surplus to deficit starting in 2001, a trade deficit that ballooned to $81 billion by 2010. Moreover, the United States has been steadily losing research and development activity linked to manufacturing and associated highly skilled jobs to other nations. As was made clear in the President’s Council of Advisors on Science and Technology (PCAST) report, “Ensuring American Leadership in Advanced Manufacturing,” this decline extends to advanced technologies invented in the US, and is not only the result of low wage competition. It is also apparent that technology innovation is closely tied to manufacturing technology and advancement.

Nanomaterials based nanomanufacturing involves adding materials selectively such that no material removal is needed.

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**ENVISION:**
**AN INNOVATIVE NEW ERA OF NANOMANUFACTURING**
Many of us have heard about the great impact nanotechnology will have on green energy, medical treatment and therapy breakthroughs, as well as advanced nanoelectronics. However, one of the biggest impacts of nanotechnology will be on manufacturing.

Present fabrication facilities that manufacture nanoscale devices such as consumer electronics costs $5–$10 billion. This high cost of entry is a barrier that completely shuts out small- and medium-sized businesses. Dramatically lowering such barriers would spur innovation and possibly lead to the creation of entirely new industries. A directed nanomaterials-based nanomanufacturing factory could be built for as low as $25–$50 million, a fraction of today’s cost, making nanotechnology accessible to millions of new innovators and entrepreneurs and unleash a new wave of creativity in the same way the advent of the PC did for computing.

Imagine if any small- or medium-sized company could manufacture nanoscale systems and devices at a small fraction (e.g., one hundredth) of today’s cost. This change would unleash a wave of creativity by making nanoscale manufacturing accessible and affordable for a range of industries in the same way as the advent of PC technology did for the computing industry, and in the process revitalize American manufacturing. Dramatically lowering such barriers will spur innovation and the creation of entirely new industries by: creating an entirely new tool set for manufacturing nanoscale structures; drastically reducing the cost of nanomanufacturing equipment and tools; and encouraging long-term sustainability by reducing energy, consumables, and waste costs.

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Many of the potential applications and products will be made using very different technologies and processes than what we are used to. We are already seeing early signs of shifting the manufacturing of devices and other products from vacuum-based processes. For example, some photovoltaics manufacturers use screen printing and some display applications use inkjet printing of circuit patterns.
Rethinking Manufacturing

Manufacturing is the process of converting raw materials, components, or parts into finished products. Specifically, it is the process of adding or removing materials by means of a large-scale industrial operation, which can take place at macro, micro or nanoscales. Macromanufacturing involves cutting, coating, shaping, welding and assembly of various parts with most processes conducted at room temperature and pressure. Current micro and nanoscale manufac- turing involves deposition (thin film using chemical or physical processes), etching, polishing, assembly, packaging, and wire bonding. Nanomaterials-based nanomanufacturing involves adding materials selectively such that no material removal is needed, thereby both reducing waste and the number of required processes.

For example, the NSF Nanoscale Science and Engineering Center for High-Rate Nanomanufacturing’s toolbox of assembly processes offers high-rate, bottom-up, directed, and precise assembly of nanoelements (such as carbon nanotubes, nanoparticles, and polymer nanostructures). All processes are conducted at room pressure and temperatures, even in modest clean room facilities. The technique is capable of making nanoscale systems and devices with unique properties harnessing the individual and synergistic properties of underlying nanomaterials, which is not possible using current manufacturing technology limited to silicon compatibility. This
manufacturing approach is compatible with present micro and fabrication techniques, allowing it to be used to complement existing foundries or fabrication facilities and enable them to use nanomaterials at the nanoscale.

Nanomanufacturing Using Directed Assembly

Directed assembly can be used to assemble a wide range of nanoelements including nanoparticles, nanotubes, and polymers. However, to have directed assembly, the assembly must be guided to produce the right structure or pattern that will represent the device circuitry. To do that, a template that has the desired pattern and utilizes either electric field and/or chemical functionalization can be utilized to guide the assembly of the nanoelements. The template patterns or structures could include both nanowires and nanotrenches to guide the assembly. Once the assembly is accomplished on the template, the assembled structures need to be transferred to the device substrate of choice (soft or hard) where the device will be housed.

Electric Field Driven Directed Assembly

Static and dynamic electric fields can be used to manipulate and assemble nanoelements from suspensions. The static electric field (electrophoresis) utilizes the nanoelement’s charge, while the dynamic approach (dielectrophoresis) takes advantage of the dielectric constant of the nanoelement. CHN has used nanowire templates to direct the assembly from 100 to 5-nm particles, conducting polymers, and SWNTs using a patterned template. The damascene templates interconnect all nanowires by a conductive film underneath the insulating substrate, providing equipotential on all the micro and nanowires.

CHN also developed nanotrench templates to provide a uniform electrostatic charge throughout the template, enabling reliable assembly over large areas with uniformity. This technique enabled the directed assembly of nanoparticles (>10 nm) and SWNTs into nanoscale trenches (>80 nm) in a short time (30–90 sec) and over a large area (> 2.25 cm²) (Fig. 1). The geometric constraints provided by the PMMA result in alignment of these SWNTs along the axis of the trenches.

Dielectrophoretic 3-D Assembly

Truly 3-D integrated circuits based on conventional CMOS technology are hindered by fabrication related chal-
Techniques developed to selectively place nanometer-sized materials are restricted to planar substrates. CHN has developed techniques to enable low temperature integration of SWNTs and gold nanoparticles into three-dimensional architectures.

**Chemically Driven Directed Assembly**

In addition to electrophoretic driven assembly, CHN has developed several chemically driven assembly methods. These methods have primarily utilized trench templates, but new flexible templates and nanowire templates can also be functionalized for assembly.

**Assembly of High-Density Single-Walled Carbon Nanotubes on Rigid and Flexible Substrates**

The placement/incorporation of ordered arrays of carbon nanotubes onto either rigid or flexible substrates offers many opportunities for novel functional devices. CHN has developed a method for direct assembly of SWNT structures on soft polymer substrates by using a surface-controlled fluidic assembly technique.

**Directed Assembly of Polymer Blends**

Nanopatterned polymers are of interest for the fabrication of optoelectronic devices, semiconductor transistors, LEDs, biosensors, and nanolithography templates. These applications require polymer structures patterned in nonuniform geometries, such as sharp 90° bends, jogs, and T-junctions. Polymer blends are attractive as blending two commercially available polymers is cost efficient and offers a wide range of materials choices. They are not limited by block length, which facilitates fabrication of nonuniform geometries and multiple length scales on a single substrate. CHN has demonstrated high-rate directed assembly of polymer blends into non-uniform structures, with multiple length scales on a single template, and into arbitrary structures.

**Transfer**

Transfer of assembled nanoelements from one surface to another is important for the integration of nanoscale processes. Several transfer processes have been developed by the CHN including transfer to both rigid and compliant substrates. Methods employing high rate polymer processing technologies, such as injection molding and compression molding to transfer the pattern, would be ideal methods for nano-/micro-

Transfer of SWNTs. All of these processes are complementary to existing processes such as CVD, PVD, nanoimprint, or novel nanoparticle based printed inks that can be sintered at low temperatures.