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PERSPECTIVES

Nanomanufacturing and sustainability: opportunities and challenges

**Ahmed A. Busnaina · Joey Mead ·
Jacqueline Isaacs · Sivasubramanian Somu**

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Abstract New nanomanufacturing technologies, although still in research labs, present a great opportunity to drastically reduce the cost of making nanostructures on a large scale and at high-rates. Such new bottom-up directed assembly-based approaches involve adding materials selectively thereby both reducing waste and the number of required processes. Directed assembly-based processes are conducted at room pressure and temperatures which significantly reduces the cost of nanomanufacturing equipment and tools, ensuring long-term sustainability by reducing energy, consumables, and waste costs. This paradigm shift in nanomanufacturing will unleash not only a wave of creativity in sustainable nanomanufacturing but lessons learnt along the way can be used in various other sectors. Along with the exquisite technological promise that nanotechnology holds, nano-enabled products are heralded as a means for energy and resource reduction, resulting in potential manufacturing cost reductions and further, for potential improvements to environmental remediation. Sustainable nanomanufacturing will, by dramatically lowering current nanomanufacturing barriers, spur innovation, and the creation of entirely new industries by leveling the playing and ultimately leading to the democratization of nanomanufacturing.

Keywords Nanomanufacturing · Sustainability · Directed assembly · Nanomaterials

Introduction

Considerable investment and progress have been made in nanotechnology over the last decade. Much of the initial investment was justifiably focused on fundamental research, resulting in significant advancement in nanomaterials, new manufacturing processes capable of making 2D and 3D nanoscale structures, and new device concepts. However, most of today's products involving fabricated nanostructures are made using top down conventional technologies such as semiconductor manufacturing. Today, a semiconductor fabrication facility that manufactures consumer electronics containing nanoscale features costs $7–10 billion to construct. Semiconductor processing equipment cost ranges from a few hundred thousand dollars to a few million with

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A. A. Busnaina (✉) · J. Isaacs · S. Somu
NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing, Northeastern University,
Boston, MA 02115, USA
e-mail: BUSNAINA@COE.NEU.EDU

J. Mead
University of Massachusetts Lowell, Lowell, MA 01854, USA

some lithography equipment exceeding $50 million. This high cost entry barrier completely shuts out small- and medium-sized businesses. In addition, such large facilities have a huge environmental impact; for example, these facilities consume more than 4 million gallons of water per day. Dramatically lowering such barriers will spur innovation and the creation of entirely new industries. Imagine if a company of any size could manufacture nanoscale systems and devices at a small fraction (e.g., one hundredth) of today's cost. It 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 manufacturing.

Manufacturing is the process of adding or removing materials at the macro, micro, or nanoscales. Current micro and nanoscale manufacturing involves deposition (thin film using chemical or physical processes), etching, polishing, assembly, packaging, and wire bonding. Successful nanoscale manufacturing that leads to commercialization of nano-enabled products requires robust, additive, and multiscale nanomanufacturing systems that can be used to make a diverse array of applications. There are already signs of the shift in manufacturing of devices and other products from vacuum-based processes. For example, some photovoltaic manufacturers use screen-printing, and some display applications (already commercialized) use inkjet printing of circuit patterns. Recently, the use of 3D and electronic printing additive technologies is on the rise, however, they are slow and are only capable of microscale resolutions, so products requiring higher resolution or large sizes take a very long time. In addition, these printing technologies are top down processes and cannot be scaled down to enable the manufacturing of nanostructures. Even with today's slow electronic printing and lower resolution, they still offer significant savings compared to conventional (semiconductor manufacturing based) electronics. For example, the cost of a printed integrated sensor-plus-digital-readout device is 1/10–1/100th the cost of current silicon-based systems (Ernst 2012).

Of course, success of an emerging technology is not dependent on the technology alone. Ethical, legal, and societal implications (ELSI) for nano-enabled products must be weighed with the technological advantages. Unintended implications of nanotechnology to human health and the environment should be avoided by early examination of the effects of nanoparticle releases throughout the product lifecycle. Many organizations and research labs are striving to find safe practices for working with nanomaterials in light of the uncertainties of exposure (Murashov and Howard 2011; NIOSH Workplace Safety and Health Topics, National Institute of Occupational Safety and Health, Center for Disease Control and Prevention, http://www.cdc.gov/niosh/topics/nanotech/, Accessed July 5 2013; OECD series on the safety of manufactured nanomaterials, organisation for economic co-operation and development, http://www.oecd.org/science/nanosafety/publicationsintheseriesonthesafetyofmanufacturednanomaterials.htm Accessed July 5 2013). The environmental health and safety (EHS) implications remain paramount to the responsible commercialization of nano-enabled products.

Sustainable nanomanufacturing opportunities

New nanomanufacturing technologies, although still in research labs, present a great opportunity to address these manufacturing challenges. New directed assembly (Vossmeyer et al. 1997; Polleux et al. 2004; Park et al. 2001; Davis et al. 2001; Zirbs et al. 2005) and transfer approaches (Allen et al. 2006; Ahn et al. 2006; Kim et al. 2010) involves adding materials selectively such that no material removal is needed; thereby both reducing waste and the number of required processes. These directed assembly processes offer high-rate, bottom-up, directed, and precise assembly of nanoelements (such as carbon nanotubes, nanoparticles, and polymer nanostructures). These techniques are capable of making nanoscale systems and devices with unique properties that harness the individual and synergistic properties of underlying nanomaterials. Most of the directed assembly and transfer processes are conducted at room pressure and temperatures. This drastically reduces the cost of nanomanufacturing equipment and tools, ensuring long-term sustainability by reducing energy, consumables, and waste costs.

Such a nanomaterials-based nanomanufacturing system could be built for a fraction of today's fab cost. So why is the directed assembly-based nanomanufacturing approach lower in cost? The processes used are operated at room temperature and pressure (no vacuum or high temperature), which will provide a significant cost reduction in equipment, energy, and maintenance costs. Most of the tools used to conduct the directed assembly processes are simple—mostly dip coating or spinning-based processes—significantly reducing tool and operation costs. Also, with reduction of the number of process required the consumption of water, material, and energy would be significantly reduced. Many of the directed assembly and transfer processes are scalable and high-rate.

Opportunities exist at the initial stages of product design to create environmentally benign products, beginning with assessment of nanomanufacturing practices (Eckelman et al. 2012; Dahlben et al. 2013). The economic and environmental assessment of products during their manufacture, use and end-of-life disposal is encouraged to establish best practices now—while the processes are under development—instead of after intended consequences arise.

Sustainable nanomanufacturing processes

Various processes for large scale manufacturing of nano-enabled products have been developed. In this paper, the author will focus on efforts developed at the NSF Nanoscale Science and Engineering Center for high-rate nanomanufacturing (CHN). The CHN efforts focused on processes that utilize directed assembly and transfer for assembling various types of nanoelements on different substrates with precise addressing and orientation. Pre-patterned templates are used to direct the assembly of nanoparticles (as small as 2 nm), conducting polymers (Wei et al. 2006), and single wall carbon nanotubes (SWCNTs) (Xiong et al. 2005). CHN has also developed damascene templates to provide a uniform electrophoretic force throughout the template for any pattern size enabling reliable assembly over large areas. These techniques enabled the directed assembly of nanoparticles (Xiong et al. 2006) and SWCNTs into nanoscale patterns in 1 min and over a large area (in inches) (Makaram et al. 2007a). Moreover these assembly techniques are used to assemble more than one type of nanomaterial on the same substrate for increased functionality and performance.

Truly 3D integrated circuits based on conventional CMOS technology are hindered by fabrication related challenges. Introduction of nanomaterials into preexisting systems and architectures can result in superior performance. However, techniques developed to selectively place nanometer-sized materials (Nihei et al. 2004; Chen et al. 2006) are restricted to planar substrates. CHN has developed a hybrid technique combining both bottom-up dielectrophoresis and top-down microfabrication techniques to enable low temperature integration of SWNTs (Makaram et al. 2007b; Selvarasah et al. 2011) and gold nanoparticles (Yilmaz et al. 2010) into three-dimensional architectures. In addition, CHN demonstrated the assembly of SWCNTs into exiting CMOS platforms to create highly robust sensors for the detection of various chemicals (Chen et al. 2009, 2010).

An emerging area of commercial importance is flexible electronics, but they suffer from a significant performance drawback when compared to standard CMOS devices. Unprecedented advantages can be realized if nanomaterials are used as active elements in flexible electronics. To addresses this issue CHN has demonstrated directed assembly of SWNT structures on soft polymer substrates using a surface controlled fluidic assembly (Selvarasah et al. 2010; Xiong et al. 2009). Polymer structures patterned in non-uniform geometries, such as sharp 90° bends and T-junctions (Stoykovich et al. 2007) have also been shown. Directed assembly of polymer blends into non-uniform structures (Wei et al. 2009; Fang et al. 2010), with multiple length scales on a single template (Chiota et al. 2009) and into arbitrary structures at a high-rate has been demonstrated by CHN (Fig. 1).

Transfer of assembled nanoelements from one surface to another is important for the integration of nanoscale processes. The CHN has demonstrated the successful transfer of conducting polymers and CNTs to a number of polymer substrates (Kumar et al. 2008; Wei et al. 2006). By combining template-guided fluidic SWNT assembly (Xiong et al. 2007; Jaber-Ansari et al. 2009a, b; Somu et al. 2010) and transfer techniques (Li et al. 2011a, b) researchers at CHN has created horizontally organized SWNTs network architectures at nano/microscale on diverse substrates with enhanced functionality.

Sustainable nanomanufacturing challenges

There are many challenges facing this new nanomanufacturing technology, some of the challenges are technical and some are cultural. For example, the electronics industry has spent hundreds of billions of dollars on fabrication facilities and will not entertain

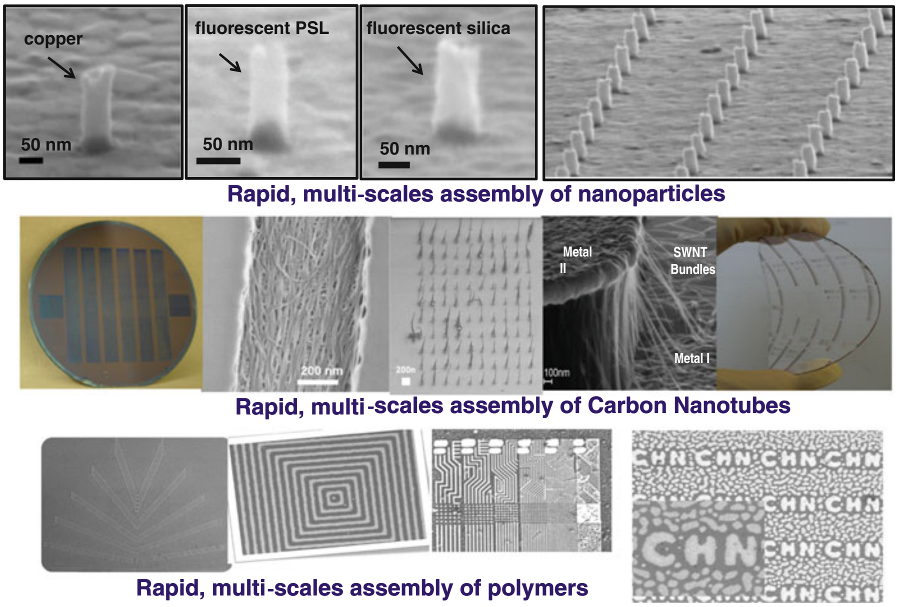

Fig. 1 Assembly of various nanoelements, including nanoparticles, carbon nanotubes, and polymers in different configuration and orientation

or consider a new manufacturing technology unless there is a remarkable enhancement over existing performance in addition to low cost.

Most of the technical challenges deal with scalability while maintaining the nanoscale properties. In macroscopic systems comprising nanomaterials, the absence of nanomaterial properties at macroscopic length scales is a huge challenge. In order to achieve this, control of surface properties over large areas while maintaining the necessary forces at the nanoscale needs to be achieved thus enabling multiscale, heterogeneous, and monolithic nanomanufacturing that is scalable, fast, and repeatable with high yield. Hence compatibility and flexibility of the developed processes for a wide range of nanomaterials-substrates needs to be addressed. In a multilayered process, i.e., where several directed assembly and transfer process are sequentially conducted for creating a fully functional device the effect of surface tension, solvent, and viscosity of suspension/solution used in individual/subsequent processes on assembly needs to be addressed. For processes involving multiple transfers, the effect of substrate compliance (for flexible substrates) on assembly, contact area, adhesion, and transfer need to be addressed.

These innovations will lead to products with embedded nanomaterials—the health and environmental impacts of which must be established throughout their life cycles. The US National Nanotechnology Initiative Strategic Plan advocates the responsible development of nano-enabled products as central to promoting scalable nanomanufacturing and product commercialization, calling for more effective use of life cycle analysis in decision-making as nanomanufacturing scales to commercial production. Given the uncertain potential hazards, it is important to identify the likely workplace and environmental exposures during manufacture, functionalization, use, and end-of-life management including recycling and disposal—to avoid any unintended consequences. Only with broader perspectives of the systems into which nano-enabled products are inserted can nanomanufacturing succeed in becoming sustainable.

Conclusion and outlook

Many applications such as sensors, electronics, energy harvesting or storage, medical devices or functional structures can be made entirely through directed assembly and transfer process platform encompassing various nanoelements with specific functionality. Concerted efforts from scientist and engineers are needed to realize this manufacturing capability. This paradigm shift in manufacturing of nano-enabled products will unleash not only a wave of creativity in sustainable nanomanufacturing but lessons learnt along the way can be used in various other sectors.

Along with the exquisite technological promise that nanotechnology holds, nano-enabled products are heralded as a means for energy and resource reduction, resulting in potential manufacturing cost reductions and further, for potential improvements to environmental remediation. A systems approach to implementation will allow for responsible and effective commercialization of these emerging industries. Sustainable nanomanufacturing will, by dramatically lowering current nanomanufacturing barriers, spur innovation and the creation of entirely new industries by leveling the playing and ultimately leading to the democratization of nanomanufacturing.

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