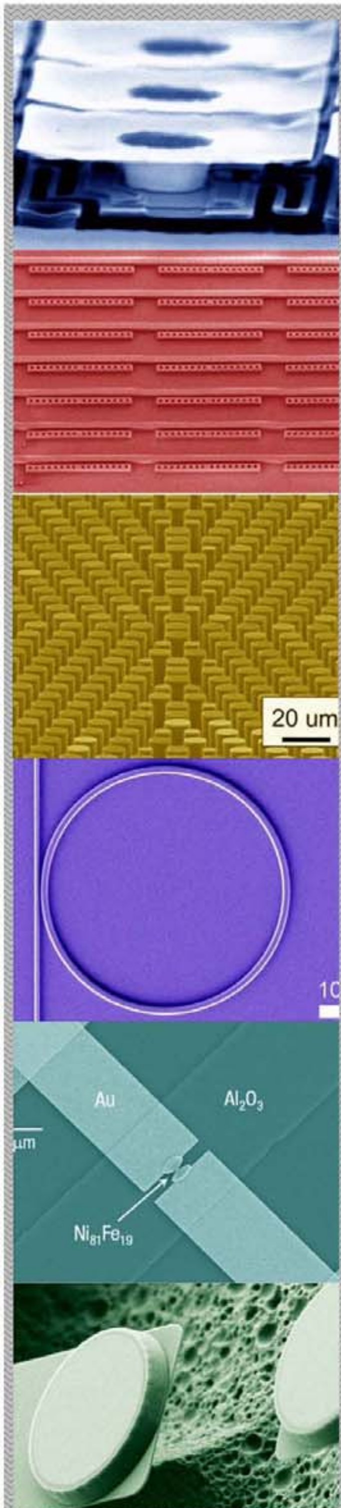

Synergies in NanoScale Manufacturing & Research

A two day workshop held at

Cornell University, Ithaca, NY 14853

January 27- 29, 2010

Workshop Summary

Cornell University
Cornell NanoScale Science and Technology Facility

NNIN
Nanoscale Science, Engineering & Technology

National Nanomanufacturing Network

NSF

Workshop Report: Synergies in NanoScale Manufacturing & Research

held at Cornell University, Ithaca, NY, January 28 and 29, 2010
Sponsored by NNIN, NNN[2], and CNF[1]

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I. Executive Summary

CNF hosted a two day workshop, **"Synergies in NanoScale Manufacturing and Research,"** held on the Cornell University campus **January 28-29, 2010**. This was a by-invitation-only working group intended to generate active discussion in the issues related to bringing emergent tools, processes, and materials into commercialization. The speakers, moderators, and attendees were selected from across the country and from industry, academia, and government labs to bring a broad range of expertise and experience to the group discussions. **The workshop was sponsored jointly by the NSF's *National Nanomanufacturing Network* (centered at U Mass Amherst), and the *National Nanotechnology Infrastructure Network*.** The program effort was led by Don Tennant, Sandip Tiwari , and Lynn Rathbun from Cornell University and Mark Tuominen and Jeff Morse from U. Mass. Speaker topics ranged from roll to roll production of flexible electronics, mass methods of producing bit patterned magnetic media, ways to manufacture in silicon with atomic precision to groundbreaking methods of making measurements of structural properties in complex materials. We also heard reports on several new means of highly specialized drug delivery, the possibility of mass production of carbon substrates for electronics, a new class of photochemicals compatible with organic materials, and more. Each day's presentations were followed by group and breakout discussions centered on questions and topics stimulated by the various speakers. The main themes dealt with issues such as infrastructure investment, standardization, development of metrology and quality monitoring methods, and scalability of many of the emergent technologies.

Discussion Points:

- Key initial application areas/first-to-market opportunities
- Costs and economic factors
- Standards
- Process modeling
- Metrology needs
- Intellectual property issues
- Funding Gaps

General Findings:

- Identified issues common to a number of emergent technologies that are potential impediments to commercialization.

- Instruments in labs are not being standardized and infrastructure to support scale up is not progressing at the same rate as the prototype systems.
- heard of possible new fields emerging from academic labs for scalable materials (such as graphene and roll to roll electronics and pharma).
- In the area of mass production of imprinted structures, a likely high impact industry will be in the bit patterned magnetic storage sector. Approaches including combining electron beam lithography and block copolymers may be employed to create extremely high density island material. The business models/ value chain likely to be very different.
- NNIN laboratories are eager to play a role as enabling facilities for pre commercialization work to be done.
- Important new instrumentation suitable to support metrology needs were demonstrated but issues related to access for widespread adoption is uncertain.
- IP remains a concern on several levels.

II. Workshop Detailed Summary

Workshop Introduction and Stated Purpose:

Workshop participants were welcomed by Professor Sandip Tiwari, Director of the National Nanotechnology Infrastructure Network (NNIN); Donald Tennant, Director of Operations and acting Director of the Cornell NanoScale Science and Technology Facility (an NNIN site); and Mark Tuominen, Professor of Physics and Co-Director of the Center for Hierarchical Manufacturing and MassNanoTech at the University of Massachusetts, Amherst.

Sandip Tiwari noted that the NNIN makes equipment available so it's affordable to industrial, academic and government users. Academic scientists and people from industry can exchange ideas while working at NNIN sites. One thousand PhD students and 350 industry researchers rub shoulders there. Because of the size of the network, it can also do other activities such as educational outreach. He also noted that there is a big gulf between research and manufacturing, which is why dialogue is so important. This workshop is one of four that NNIN organizes each year to facilitate this important open discussion.

Don Tennant stated that this workshop is intended to be something like a SEMATECH workshop, with breakout sessions where people will discuss points raised by the talks and try to come to a consensus. He recapped a message from the 2009 International Conference on Nanoimprint and Nanoprint Technology (NNT), in which Fabian Pease (Stanford) spoke about NNT losing the propaganda war for funding to competing technologies. NNT proponents were advised to win over the mindset of management, investors, and the research and development community. The best technology does not always win so strategic arguments matter. The stakeholders in this field include researchers, manufacturers with research issues, facilities which would like to play a role in moving emerging technologies to commercialization, and funding agencies. Mark Tuominen discussed the National Nanomanufacturing Network (NNN), a catalyst to support and develop communities of practice in nanomanufacturing. It is a partnership between academia, industry and government, and the website is www.nanomanufacturing.org. There are four NSF Nanoscale

Science and Engineering Centers (NSECs) devoted to nanomanufacturing. He listed the following goals for the workshop:

- Assist with interaction between researchers and manufacturers.
- Disseminate recent progress in nanomanufacturing.
- Identify needs, challenges, and opportunities in nanomanufacturing.
- Identify clusters of focused activity.
- Create strategies to strengthen and fill gaps in the nanomanufacturing value chain.

Mark Tuominen presented ideas about the infrastructure needed for nanomanufacturing, in four areas: information, tools, know-how, and roadmaps. Questions for participants to consider about technologies presented at the meeting, and also for evaluating any proposed nanomanufacturing effort:

- Can the technologies presented be done at high enough scale and throughput to be commercially viable?
- If not, what are the scientific and technical barriers to commercialization, in terms of throughput, quality, design or performance?
- Are tools and material feedstock available for the desired manufacturing scale?
- Will it have adequate reproducibility and reliability?
- What pieces are missing in the value chain?

III.Group Composition:

~ 40 Participants came from the following institutions:

Carnegie Mellon University
Cornell University
EV Group
GE
Hitachi Global Systems
HP Labs
Industrial Collaboration Commercial Partnerships
IST
Kionix
Liquidia Technologies
NIST
Northeastern Univ
RPI
SWeNT
U Houston
U Mass Amherst
U Mich
U Texas
UCLA
UIUC
Yale University
Zyvex Labs

IV. Presentations Categorized

You can view the talks presented at the meeting on the NNIN website: http://www.nnin.org/nnin_snmr10_event.html. Technologies presented by participants, assigned roughly to categories of commercial readiness, included:

Basic research:

- Spectroscopic Imaging STM for Visualization of Complex Electronic Matter -- J.C. Seamus Davis

Applied research

- Nanoimprinting with amorphous metals -- Jan Shroers
- Solid State Ionic Nanomanufacturing -- Nicholas Fang
- Self-assembled Polymer Templates for Device Fabrication using Roll-to-Roll Platforms -- Jim Watkins
- Infinite length, meter wide, n-layer graphene and ultrathin graphite: a Nanomanufacturing Challenge -- Rod Ruoff
- Developing high-throughput roll-to-roll nanopatterning processes as a viable approach to nanomanufacturing -- L. Jay Guo
- Positioning at Nanoscale -- John Wen
- Atomically Precise Manufacturing will happen: The case for this decade -- John Randall
- Metrology and Materials for Nanoimprint Technologies: Needs and Prospects -- Chris Soles
- Accurate carbon nanostructures for nanoscale electronics and optics -- Jiwoong Park
- From Particles to Materials (including fluorescent core-shell silica nanoparticles) -- Uli Wiesner
- New Dimensions in Patterning: Placement and Metrology of Chemical Functionality at All Scales -- Shelley Claridge
- Nanoscale Synthesis and Layer-By-Layer Assembly of High Performance Fuel Cell Materials -- Andre Taylor

Industrial research and development

- Moving Roll to Roll processing from the Lab to Manufacturing -- John Maltabes
- Patterned Media: A Precision Challenge for Nanotechnology -- Neil Robertson
- Orthogonal Lithography -- Chris Ober
- Nanomanufacturing for Industrial Applications -- James Ruud

Commercial production

- Commercializing Specialty Carbon Nanotube Materials for Coatings and Composites -- David Arthur
- Liquidia's Use of PRINT® Technology to Produce Precisely Engineered Particles on a Commercial Scale for Life Science and Materials Science Applications -- Mike Hunter
- Super-Hydrophobic Nano-Composites -- Jeff Chinn

V. Discussion

Day 1 Summary

After presentations on roll to roll nanomanufacturing, Nanopositioning, new Nanoimprinting methods and materials (including amorphous metals, solid state ionic materials, proteins and functionalized nonmaterial's), metrology, self-assembly and layer by layer assembly, attendees discussed the following topics:

Key Insertion Points for Technologies and Application Areas Impacted

Some first-to-market opportunities that would provide talking points for countering the propaganda war from lithographers include:

- Data storage/Bit Patterned Media
- Flexible lighting and displays
- Solar cells/photovoltaic's
- Fuel cell materials and catalysts
- Transparent electrodes
- Li-ion and other batteries
- Ultracapacitors
- Life sciences
- Super low cost displays
- Non-conventional displays
- LED solid state lighting
- Drug delivery devices
- Microfluidics
- Coatings, formulations of nonmaterial

Colloids, with fine chemical composition and size control, and nanoparticles for biomedical applications are another promising area. There is a NIH/NIST effort underway for metrology of nanoparticles. Production of extremely thin films such as **graphene**, on large scale for applications like display electrodes. Roll to roll work in Japan (arXiv:0912.5485v1) is just starting but there is not much activity yet in the U.S. HP's crossbar technology was mentioned, but it was pointed out that it's all red on the ITRS Roadmap; solar cells, lighting and displays are more feasible. It was suggested that the driver application for **roll to roll** (R2R) technology would be flexible solar cells like those made by Kumara; also batteries and lighting. Lighting is a very big volume application. If there is a lot of variety and low volume, you don't want R2R; for R2R you want large volumes of the same thing, e.g. printed lighting panels. It should be possible to produce two similar products in the same factory, like lighting and solar and displays (but displays need many fewer defects). This would be similar to producing memory chips and processors in the same fab.

Layer by Layer assembly. Nanostrata has sold perhaps 100 machines; this has sped research. Is it possible to do this by gas phase approaches? ALD with monomers is perhaps an analogy.

Masters for nanoimprint

The *general availability of masters* for nanoimprint was discussed. It is possible that secondary "masks" could be as good as the original master. It requires infrastructure. Molecular imprints ran the show for nanoimprint for a long time and told mask shops how to do it. Roll to roll is a free-for-all now, because there are no standards yet. Again it's a question of money to adapt existing systems to this new setup. An engineering research center/nanofoundry that makes imprint masters in arbitrary formats could be a way to make masters more readily available. Are there other methods of making masters? For example, if one could have any master in a roll, with good seams or no seams, this could be a big enabler. Right now it seems as if there is no true alternative to electron beam lithography, but if one had the "perfect" block copolymer, that might work. More work on block co-polymers is needed, including some that work at smaller length scales. Interface management, with selective removal of one phase might work. Block co-polymer inorganic options perhaps ought to be explored. Functionality from the inorganic component could be integrated with structure from the polymer component. The communities are not even talking with each other now; broadening the discussion is needed.

Metrology
Metrology is needed for producing nanoimprint masters and for replication. Metrology criteria depend on the process. For many processes, long-range order and periodicity are not needed. It's necessary to characterize the disorder, or more generally, the structure. To make surface area measurements of thin films that have, for example, high rugosity, development of 3D metrology is needed, particularly at small length scales. Technologies that could do this include TEM-tomography and synchrotron-based computed tomography, like Xradia's MicroXCT X-ray CT scanner. Different methods yield different surface areas depending on their treatment of or ability to detect occluded volumes. Compositional analysis is needed, especially for life sciences applications. For real-time process control, measurement speed needs to be fast. It may not be necessary or possible to interrogate every square nanometer. Control methodologies that use feedforward or feedback, when relevant, need to be developed. Defect detection will continue to be important.

New innovations
Sub-lithographic methods are being developed for graphene nanoribbons. More of these methods and other innovations are needed.

Process Control and Metrology for Specific Processes
Some discussions of process control, predictive modeling and metrology centered around specific processes.

- **Patterned Media on Hard Substrates**

Patterning and Assembly on Hard Substrates *requires long range order, features ~13nm, resolution~1nm* there are limits for long range order and defects with BCP self-assembly. Both circular patterns and square patterns are needed. Consider pattern jitter, error correction in making master

- **Metrology and inspection requirements for Patterned media**

With BPM, defects in long-range order are hardest to detect. Scale/area for patterned media can be addressed with present imaging/inspection tools. Critical offline inspection for Master is needed, not quite so critical for copies. Inline monitoring of defects needed for production

- **Roll-to-Roll and Large Area Substrates**

Process control, Patterning and Assembly of Roll-to-Roll and Large Area Substrates – need to control: For nanoscale NIL, resist adhesion and pattern fidelity are issues. Custom photopolymers have to be developed to address them.

Etch-use endpoint or etch stop: For control and feedback for wet etch, HP uses a send-ahead piece. For dry etch, they have an optical microscope and video system in the chamber to see if it's done; you could easily integrate a laser endpoint detection system. They are etching polymers, amorphous Si and silicon oxide.

BCP Self-Assembly: long range order, drying time, rapid organization

Master fabrication-quality, repeatability. Infrastructure needed

Other assembly approaches (e.g.; LBL) need to control process time and efficiency, materials utilization, cost.

Metrology, standards and inspection requirements for Roll to Roll:

  - defect inspection-pattern defects
  - characterization/pattern inspection
  - laser scattering/particle size distribution
  - final yield as means to identify defects
  - cost involved for now at micron scale for adapting tools to R2R web platforms
  - smallest features inspected can reach to 1 µm

Inspection can look at either nanoscale patterns, or larger scale patterns that contain nanomaterials, which is easier. The first products to come to market will have mm-scale features with nanoscale materials that are characterized before putting them into the R2R process. For example, the smallest dimension of the HP display is 1 um. For inspection, handling systems have to be designed to adapt existing inspection systems that can see 50 nm on a wafer, so they will work with R2R. Money is the biggest challenge.

Self-Assembly Approaches

Process Requirements for Assembly Approaches:

What's needed for predictive modeling: hybrid materials don't have models for behavior of solvents vs. temperature, block copolymers do.

The radius of curvature of templates for patterned media has to be large enough to fool them into bending. Nobody has patterned whole disk, but a 1 mm strip all around a disk has been done.

Metrology and Inspection Requirements for Assembly Approaches:

Order/disorder pattern critical dimension analysis on web based platforms

Composition and homogeneity

Modeling of process kinetics would be helpful to predict process window

Block copolymer needs: it gets a lot trickier when going from coupons to web to keep long-range order; there's nothing available now.

Batch to batch variability has to be taken into account at large scale also. In labs you tend to use a single batch for a long time so it doesn't have variability. This is why HP are doing qualification of supplies when they come in. In lithography, photoresist varies from month to month, oxides and other thin films have less variability. UV cured resist is also less variable. Smaller suppliers are more interested in creating qualified materials than large suppliers.

Nanoparticles for Life Sciences

Process Requirements for Life Sciences include

- uniformity, homogeneity
- new approaches to forming masters for nanoparticles < 100 nm in size
- process models need to include fluid flow, temperature effects
- narrow process window before scale-up of new materials sets/compositions
- Metrology and Inspection issues for Life Sciences include
- material composition inline
- flexible transparent substrates
- averaging image of uniformity, material fill
- characterizing master, tooling (offline)
    - inline measurements (spatial density, height in filling mold, pulling particle out of mold)
    - map harvested particles
    - tools for surface chemistry analysis(functionalization, coatings)

For PRINT nanoparticles there is still a need to inspect masters but they are looking for something inline to inspect an array of particles for uniform height and their spatial density (missing particles). They don't know if other inspection methods will work, for example spectroscopic ellipsometry has trouble with the birefringence of PET substrates.

You would like to do mass spectrometry on molecules on a surface.

Nano-positioning (in 2D, in 3D)

For nanopositioning of colloidal particles, the dispersion in size, etc. of such nanoparticles is an issue.

Standards

How will standards be formulated? There are not a lot of companies trying to do the same thing yet, as there are in semiconductors; in the beginning of semiconductors it was similar to the present situation in nanomanufacturing. HP doesn't want to pay for all the infrastructure, but are willing to license technology so there are standards.

Missing connection(s) between precision engineering & nanomanufacturing community.

There are opportunities for bringing the precision engineering community together with the R2R community, for example, through the FlexTech Alliance.

Perhaps a center is needed, focused on making NIL “prints”. Like a “Nano-Foundry” or a “nano R2R fab”.

Speedup and economics

Comparing EUV and NIL, EUV can do overlay and it can do throughput. These are the big issues on the factory floor. Compare nanopatterning, NIL specifically, with EUV. What are potential or real advantages of NIL or other nanopatterning methods vs. EUV or commercially used methods.

- **Driving Factors:**

  EH&S: processes developed in the lab are not necessarily compliant with materials supply, supply chain yet.

  Organic materials vary, so there is a need for qualification of supply and the supply chain.

  New company opportunities: there is more interest in developing new materials (custom resists, coatings…etc.)

- **Cost/Economic Factors**

  ESH –regulatory and MSDS certification for supply chain (custom resists, materials, chemicals). A lot of people have not even considered the EH&S issues in the final manufacture of products -- someone might say you can't use a material you want to use. The photopolymer that HP use is formulated in-house and scaling it up to be produced outside would require safety qualification; they hope to substitute something that's already in use.

  - Rate/throughput-reduce costs
  - Feature size-smaller, better control
  - Standardize-beginning materials-clean/defect free

Day 2 Discussion Summary

This discussion took place after presentations on composite coatings, industrial nanomanufacturing, orthogonal lithography, nanoparticles, commercial carbon nanotube materials, the possibility of atomically precise manufacturing, graphene manufacturing, and carbon nanostructures. The discussion touched on the following themes:

Impediments to Progress

The university-industry interface is less easy than it was 10 years ago. The university needs advice from industry; it has to be a two way conversation. There are still IP hurdles between universities and industry that make interaction inefficient. There are problems with use of university facilities and space for industrial resesearch, and collaboration agreements often have conflicting views of who owns ideas, depending on where they originated.

It is difficult to get research focusing on high-throughput methods funded by the NSF because it’s not novel enough. There are barriers for junior faculty to doing industrial-focused work, regardless of grant size; some fundamental research must be done also to complement it. The culture in U.S. universities is not very supportive of close university-industry relationships. Close and effective university-industrial interactions such as those in Korea, Japan, China, etc. are needed. On the other hand, funding by DARPA and venture capital funding is more readily available in the U.S.

Opportunities for University-Industry Collaboration

Nanomanufacturing is happening in industry now. Academics should talk to people in industry to understand the problems, both engineering and science. Metrology is one important area for collaboration. There could be funding for places to bring things together: a test bed, demonstrating the technology and all that goes into it.

University research in tip-based manufacturing approaches is needed for better tips, substrates and to investigate the replication potential.

There is characterization work that is easily done, to get structure-function relationships; this can be industry funded. Industry can send samples out to universities for testing. It's important to work together closely to show how to get the desired results (translation with experts present).
There are also characterization challenges, e.g. to determine properties over a large area, over macroscale.

Nanoinformatics
An issue with block copolymers (BCP) is that there are more complex choices now, but the metrology is the same as it was ten years ago. Databases for these new complex systems are needed, analogous to the bioscience area for x-ray or NMR. This needs to be developed by an instrument/software maker. A tool is needed to streamline the data workflow process (see the work of Mike Garner/NNI) –- this is an opportunity. To test out a new material (e.g. a BCP), currently requires a lot of lab manpower; there is a need to automate and get this data quickly. Build the database, even from already published data. NIST can and should help here. Construction of new tools has fallen out of favor. We need a new generation of instrument designers and builders.
The nanoHUB is an example of sharing databases, creating a platform for other areas, and a useful legacy. We want to put data from NSF-funded research into standard formats, with translation programs to other formats.

Facilities and instrumentation
Nanomanufacturing research and development can require equipment that's not currently available or has limited availability through NNIN or DOE. The Imago LEAP atom probe is one example of very useful equipment. Another example is a robot for high throughput nanocrystal synthesis (DOE Molecular Foundry). Instrument building efforts maintain and build expertise.
Some of the NNIN and DOE sites can have restrictions on materials or processes that would prevent doing some useful nanomanufacturing research there, depending on the primary function among a sites user community. However some sites have some tools that can accommodate unusual materials, including Purdue, Berkeley, UT Austin and Cornell. But tool development is rather limited in the current mission and budget parameters.

Metrology is key to nanomanufacturing development. It's needed for quality control of devices and materials (e.g. size, shape, surface functionalization) and for manufacturing scale. Both need tool and instrumentation development for advancement; central facilities can help. NIST is investing in metrology through the Technology Innovation Program (TIP), supporting scale-up and nurturing the innovators in academia. There is a need for the continued development of instrumentation for nanomaterials research, for personalized/single lab use, ultimately. It takes many years (more than the 3 years of an MRI grant) to do this. In the past, a lot of tool development was done at IBM, Bell Labs, etc. Now it would be a good fit for the DOE national labs to play a role. There would be evolution from proof of concept instrument, to commercial product, with data at high rate. NSF should have a big role, nonetheless.
The NNI is looking for commercial demonstrations. NNIN is a platform for proof of concept work by industry, taking the steps towards scale-up.

Ideas for new institutions or funding mechanisms
Collaboration
Many academic discoveries don't get to industry due to a translation gap. Getting people to talk and work together at the bench is the fastest way to get technology transfer done. Working with people from the applications side is stimulating, and students need to experience this. It does take effort to work with the real world. Media such as videoconferencing or video documentation can help the communication, especially with current students who are used to watching video clips on the web.
University-industrial interaction funds can help. A good example of a valuable university-industry relationship, which is straightforward and has few barriers is the EHS NanoSafe consortia for carbon.

Others are NNI workshops and toxicology testing at universities. The latter has issues with sharing proprietary information about materials.

Internships and sabbaticals
An internship would help students greatly and teach them how to communicate with industry. Internships are available via IGERT, but there can be other routes too. Students or postdoc could spend at least 3 months in industry to speed up university-to-industrial transfers. However this may interfere with the main mission of students and advisors to finish and write up their thesis research.
There could also be mini-sabbaticals for faculty, with a funding mechanism to support them.

National strategy
In order to help grow nanomanufacturing in a scalable manner there should be a national investment strategy to support the development of nanomanufacturing. The NSF should add to its funding criteria, currently based primarily on novelty, work to develop towards manufacturing, (scale up, etc).
There should be a dedicated platform or framework for industry-academia interactions, such as nanomanufacturing test beds and pilots which can proof out demonstrations.
A federally funded skunk works that is fast, like TIP, and focused like the Semiconductor Research Corporation (SRC) is a possible mechanism to support nanomanufacturing. A demonstration vehicle can also be a driver and promote standardization. Different applications need different standards and needs. For example, physical sciences and life sciences applications have different requirements for degrees of reproducibility, reliability. In order to focus in on the details within a specific application, focused workshops are needed instead of lumping disparate areas together. Workshops improve communication company-to-company; best practices can be promoted and pre-competitive information sharing can take place, improving efficiency in R&D.

IP impediments can be addressed by consortia to establish a standard IP agreement, like the SRC. A consortium can also develop standards and define goals. Having a focus leads to outc

VI. Analysis

The meeting focusing on synergy between research and manufacturing was successful partly through its diversity - traditional and non-traditional people, academic and industrial, and different disciplines, but also because of the room environment, organization of sessions, and limit on the number of attendees. The talks represent the starting discussion points among the attendees, which carried through the afternoon breakout sessions, the feedback sessions, and in the concluding discussion session.

Most of the academics know research, some have an understanding of manufacturing needs, but success in manufacturing also depends on having the right application with ample demand and production efficiencies (of cost, throughput, etc...). Research can provide new techniques for prototyping and demonstrating their useful characteristics. For a successful manufactured product, there has to be a demand (or a need), and an effective manufacturing approach. The jump from research to manufacturing can be a large jump with numerous - scientific, technical, economic, societal, ... barriers in between.

Within the technical context, the task then is to overcome the gaps and to span the scale up that is needed from research to manufacturing. For nano, the technical approaches for different applications can vary greatly and exhibit unique strengths and weaknesses (research opportunities) that need to be surmounted. Example of the latter: bottom-up approaches have poor long range order and fair amount of variability and defects (e.g. in self-assembled block copolymer approaches), while top-down approaches can involve expensive infrastructure and are largely unforgiving to defects (e.g. our traditional lithography in electronics).

The workshop helped highlight where we might map characteristics to needs to potential manufacturing solutions. Often we can identify several alternatives for applications so that one of the applications finds the right time and place for success.

Physical and Life Science applications often have different characteristics and therefore are likely to have different needs. This translates into niche opportunities for research techniques developed by physical science research making the jump to commercialization in different fields (eg. see Liquidia presentation) .

Electronics as an area of application demands exquisite control of variability and defects. Quality control has just not been good enough, and although a very large application area, any new or radically different approach will meet with a high barrier to entry and likely require an industry consortium to succeed.

Given the above observations, there are places where the current state of control and the new approaches can be fruitful and areas worthy of pursuit where manufacturing can be potentially highly successful and academic research a significant contributor to that success.

Some Examples:

1. Major applications where variability and lack of long range order are not a major detriment include lighting - solid state and organic, photovoltaics, fuel cells and batteries, ultracapacitors, coatings, ... Possible novel manufacturing techniques appropriate to these range from roll-to-roll to bottom-up assembly.

2. Major applications where shapes are important, often with dimensional control less critical or more forgiving, and volume production needs ranging from small to large. An example is drug delivery through inhalation. Roll-to-roll here for nanoscale shaped compounds manufacturing would be very suitable.

3. In electronics area, the possibility of marrying bottom-up with top-down in creating bit patterned media where an adequate compromise is obtained between the characteristics of these two different approaches and both long and short range order achieved.

The workshop looked extensively at this match of applications to characteristics needed to possible manufacturing solutions as suggested by research findings. The underlying thought was that if there are a few appealing possibilities of applications for a technique (and its variations) where the characteristics needed and achieved match, then it has a potential for success. The item d.1 above points to many with variability from bottom-up approaches being potentially acceptable.

Many of these also present interesting research challenges. Some of these discussed included:

1. Diagnostics in nanostructures - sizes, shapes, compositions, ..., etc. in situ as well as ex situ. Most organic assemblies have these variations and we do not have adequate characterization tools.
2. Metrology in processing - e.g. in roll-to-roll and then adaptive control to compensate in process for observations made. In some cases advanced methods of characterization and product monitoring are demonstrated, but only in the lab. There is no evidence of general access to the technology (see C. Soles, NIST).
3. Predictive modeling of hybrid materials. Modeling process kinetics would be helpful to predict process windows. Web-based software for analyzing critical dimensions of ordered patterns would be useful. Block copolymer models exist but there is a need for structure databases and instruments to quickly test new block copolymers.
4. Need for imprint masks - rolls or planar. These are high cost masters, but once made, the need for more is much less. So, there is a disconnection between cost of facility that makes them and the total demand. Lack of a business model and/or lack of infrastructure is an important issue.
5. There are some areas where breakthroughs are potentially on the horizon, but a major application not yet demonstrated. Two methods of large scale graphene production were presented that show such promise (see talks J. Park, R. Ruoff).