John N. Randall, Zyvex Labs

Subject: Comments on NNI Strategic Plan
From: John Randall <jrandall@zyvexlabs.com>
Date: 12/16/2013 12:46 PM
To: 2014NNIStrategy@nnco.nano.gov
CC: Lisa Friedersdorf <lfriedersdorf@nnco.nano.gov>, "david.ricketts@ncsu.edu" <david.ricketts@ncsu.edu>, "S.V. Sreenivasan" <sv.sreeni@mail.utexas.edu>

Dear National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology;

First of all thank you for the opportunity to comment on the NNI Strategic Plan. This is an extremely important program and I appreciate the effort that has gone into the plan.

My official comments are in the attached Document: NNI-Comments-JNR.pdf, where I have made some specific recommendations with respect to the language in the text. These are relatively minor, but I believe important changes, that would emphasize two main points:

1) Precision in manufacturing at the nanoscale is key to effectively controlling and exploiting the unique phenomena that are available in this size regime.

2) There is an opportunity to develop top-down fabrication techniques that exploit the quantized nature of matter to achieve a manufacturing technology with unprecedented precision and one that would enable the commercialization on many nanotechnology applications.

My comments are centered on the physical precision of fabricated/manufactured nanostructures. The fabrication and metrology tools with the highest available precision must not only be developed, but must also be widely available through the NNI Infrastructure to those who can exploit them in academia and industry (especially small companies).

The concept of precision is important in other aspects of the plan such as the signature initiative on Nanotechnology Knowledge Infrastructure which helps organize and quantify the data into readiness levels. This will be an invaluable tool in guiding those brave souls who are developing the nanotechnology applications and products. With regard to this subject, I will be so bold as to also include the report of a workshop “Enabling Nanofabrication for Rapid Innovation” (ENRI). The report is attached as ENRI-2013-Report-V1.pdf.

While I believe that the report contains much valuable information about commercializing nanotechnology, I call attention to the recommendation to create and use targeted roadmaps for subsections of nanotechnology commercialization. This recommendation would be to create and fund efforts to collect pertinent information about the required specifications of the application, the approaches to manufacturing, identified solutions, technology gaps, etc. This information would prove extremely valuable to both researchers and developers and could be fed into the Nanotechnology Knowledge Infrastructure. The section on the roadmapping process is only about 1 page and is booked marked in the document.

John N. Randall, Zyvex Labs

Regards,

John
--
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President
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Attachments:
NNI Comments-JNR.pdf 13.5 KB
ENRI-2013-Report-V1.pdf 1.7 MB

John N. Randall, Zyvex Labs

Comments and suggested edits of the NNI Strategic Plan

While overall an excellent document, there is an area that I believe is not given sufficient emphasis. That area is the precision of fabrication/manufacturing methods. If the value of nanotechnology is: *"at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications."* (Page 1 Lines 8-9), then the precision of the size control should be given significant emphasis when trying to exploit these unique phenomena. For instance, quantum dots are interesting because of their quantized electronic states, but imprecision in their size leads directly to imprecision in the level of these electronic states. While there are numerous places in the plan where precision might be considered implicit, let me suggest specific examples where this could be made far more explicit. I would suggest the following changes where the new text is underlined:

Page 27 Line 27 Scalable, repeatable, and cost effective manufacturing methods that achieve high relative precision at the nanoscale are required to move the technology from the laboratory into commercial products.

Page 28 Line 31-32 Promote the development of robust, scalable, high relative precision at the nanoscale nanomanufacturing methods necessary to facilitate commercialization.

Page 46 Line 20 … must be accomplished with nanoscale precision in a controlled and sustainable ...

Further, there is an opportunity that is also being ignored. When dealing with the 1-100nm range the impact of the quantized nature of matter is significant. Most nanofabrication methods attempt to deal with matter as if it is infinitely divisible and are contending with rather than taking advantage of the fact that matter is composed of atoms and molecules. Atomic Layer Deposition (Epitaxy) is an approach which is a counter example, but this achieves Atomic Scale precision only in one dimension. The closest the plan comes to acknowledging the need for Atomic Precision is not in the plan but in Appendix B:Page 73 Line 24 :*The ability to make nanoparticles and structures with exquisite atomic-level control.* I would propose putting something specific in the plan:

Page 42 Insert sentence starting in line 35. Research into fabrication processes (leading to manufacturing tools) that allow the creation (manufacturing) of designed 3D nanoscale structures/devices with high precision at the nanoscale with the eventual goal of absolute precision in terms of number type and chemical bonding of atoms in the 3D design.

There is excellent work being done on achieving atomic scale precision in growth dimensions, lateral dimensions, as well as all three dimensions, but much of that work is going on outside of this country (Michelle Simmons, Robert Wolkow, to name just two). Bottom up approaches (DNA Origami, etc.) are extremely worthwhile, but have definite limitations that don't exist with top down approaches that fabricate robust inorganic materials. Technological rather than scientific enquiry is beginning to drive investigation into atomic scale precision fabrication/manufacturing: quantum computing, post CMOS nanoelectronics, DNA sequencing, to name a few. But atomic precision fabrication that exploits the quantized nature of matter (both bottom up and top down) is in its infancy and would benefit (along with our country) with some targeted programs which, in my opinion, the NNI is currently failing to adequately support.

Respectfully submitted: John N. Randall – President – Zyvex Labs

August 18-21, 2013
Silverado Resort, Napa, California

Enabling Nanofabrication for Rapid Innovation

(Developing the tools for 21st Century Manufacturing)

Workshop Final Program

Co-Chairs

John N. Randall, *Zyvex Labs, USA*

S.V. Sreenivasan, *University of Texas, Austin, USA*

Technical Program Chair

David Ricketts, *North Carolina State University, USA*

Sponsored by

Enabling Nanofabrication for Rapid Innovation (ENRI) Workshop Held in Napa Valley, CA, August 2013

This document is the final report of the workshop on Enabling Nanofabrication for Rapid Innovation (ENRI) which was held August 18-21, 2013 at the Silverado Resort in Napa, California. The workshop was very effectively organized by Katharine Cline and her team at Preferred Meeting Management. This workshop was sponsored by:

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Index: Page

Enabling Nanofabrication for Rapid Innovation (ENRI)
Workshop Held in Napa Valley, CA, August 2013

1. Problem Statement:

The semiconductor industry infrastructure provides incredible capabilities in the sense of process performance and control, process speeds, and yield and is particularly suited for high volume production of CMOS devices such as micro-processors and memory. If a designer is interested in creating innovative devices, foundries offer the capabilities of fabricating ASICs. However, the designers are highly constrained by design rules, choice of substrate size and substrate materials, and choice of advanced functional materials that can be integrated into the devices.

The ENRI workshop participants concluded that this highly constrained semiconductor fabrication environment stifles innovation. For innovative manufacturing, the workshop participants concluded that there is a growing disparity between tools used for semiconductor manufacturing and those appropriate for the rapid innovation required to bring exciting new nanotechnology products and applications to the market. The restrictions on acceptable substrates, materials, and processes are already a problem; and even if the equipment is made available at no cost to university and other research laboratories the supplies and maintenance can be extremely expensive. There was unanimity that less expensive fabrication equipment designed for a variety of substrate types, and for processes that integrate novel materials types is needed. Additionally, a need for a variety of nano-scale metrology tools was discussed to enable development of robust nano-scale fabrication processes. However, in the limited time at this workshop, there was no consensus established on what enabling specifications should be the focus, and how these specifications could be eased – relative to high end semiconductor tools – to allow low cost equipment to be produced.

Similarly, when asked what opportunities existed in the realm of innovative devices and systems and specific nanofabrication tools, processes, and metrology a fairly lengthy list was developed as seen below. However, although we asked for specific quantitative data in terms of capabilities beyond the state of the art, production and capital equipment costs, the scalability and gap analysis of the applications, market analysis, and barriers to innovation, the workshop participants did not have the time or resources to provide such quantitative data which could lead to actionable recommendations.

Workshop participants were also asked to consider some key questions as they relate to enabling rapid innovation in the emerging nanotechnology markets:
1) What are the national security implications?
2) What can be learned from market failures and applied to enhance opportunities for market success?
3) What would be the downside if we did nothing to improve the opportunities for rapid innovation in nanofabrication?

2. Key Recommendations:

The workshop organizing committee has identified three key recommendations based on the output of the round table discussions. These recommendations are:

1. To exploit identified opportunities for rapid invocation shown below

2. To use targeted roadmaps to identify gaps and solutions that will enable the rapid innovation opportunities identified

3. To engage federal agencies to improve the review of nanomanufacturing proposals by including more precision and scalability metrics, including more industry input, and to promote the roadmapping activities that could drive both public and private investments

2.1 Opportunities: The list of opportunities for rapid innovation (grouped but in no particular order of priority) that were identified by the round table discussions for further considerations to define targeted programs:

KEYS TO RAPID INNOVATION:

- Compress nanodevice design/test cycle – maskless lithography, novel material integration are keys
- Wikifab, network of manufacturing capabilities
- Regional, flexible pilot production facilities
- Addressing legal barriers for academia, industry, government collaboration
- Open source set of tools
- Simplified manufacturing processes – Lowering the mask count
- Massive integration of electronics with rapid 3D prototyping
- Integrating nano-materials with existing processes (e.g. nanotubes in VLSI)
- CAD tools to enable DNA, RNA self-assembly nanomanufacturing

SPECIFIC MANUFACTURING TECHNOLOGIES

- Continuous roll to roll nano-scale printing processes
- Additive/3D manufacturing at the micro and nano scale.
- Inkjet printing: additive and direct write
- Layer by layer processing (e.g. ALD) in roll to roll and other nanomanufacturing
- Atomically (and absolutely) precise manufacturing with top down control
- Rapid and inexpensive fabrication of nanoimprint templates
- Nano-materials synthesis: Pharma/bio, feedstock for other tools/processes
- High throughput e-beam/optical lithography (e.g. for DoD needs)
- Alternative patterning: Ion/e-beam, radioisotope lithography nanopatterning
- Interference lithography for periodic structures
- Better 3D metrology tools for MEMS/NEMS

- Closed loop metrology in nanofabrication – chip-scaled SPMs
- Inline metrology (<50nm)-real time -next step process variations
- Atomic GPS: atomic scale positioning over entire wafer
- Small vacuum pumps and systems, enabling small instruments
- Intelligent biosensors (wearable) especially packaging and material integration
- Etching magnetic materials

These opportunities are listed again at the end of the report, along with an additional paragraph for each opportunity to better articulate the opportunity and its impact.

2.2 Roadmaps: Any effort to rapidly innovate involves uncertainty. The organizing committee has identified the creation of roadmaps as a preferred approach to further quantify the specifications of tools and instruments needed to enable rapid innovation in specific device sectors as well as technology gaps, market information, and specifications for specific classes of nanotechnology products.

The semiconductor industry has done a masterful job of reducing uncertainty by pre-competitive road-mapping which involves establishing a set of process specifications, their evolution over time, and the identification of potential show stoppers, namely problems that have no known solutions. By creating such pre-competitive information using a panel of experts from the various sectors of the industry, and by sharing this information broadly, the industry and its vendors have benefited hugely by knowing where the industry needs to be at any given time to be successful.

While the emerging nanotechnology industry is far too fragmented to have a comparable roadmap for the entire industry, the ENRI program committee believes there is a wonderful opportunity to create highly effective roadmaps for subsections of this evolving industry. Many such possibilities were discussed in the workshop, and a specific example – that of wearable biosensors to collect medical data – is provided here. Researchers and product developers face many uncertainties in wearable biosensors, not the least of which is, what is the data reliability and accuracy that would be acceptable to the medical community? This data along with other targets for various issues including manufacturing, testing, and market issues could be developed by an individual firm, but would be far more valuable to the industry in general if a government or consortium funded organization would make a concerted effort to work with the medical community, vendors, and interested companies to generate a consensus for targets to guide researchers and product developers.

Another cogent example is the development of low-cost nano/micro fabrication tools to enable relatively inexpensive fabrication facilities for rapid innovation. For a variety of tool sets a road-mapping process could identify what specifications would be acceptable to a targeted group of researchers and potential manufactures.

These road-mapping efforts would need to be ongoing programs that updated the roadmaps on a continuous basis to keep abreast of new developments and needs. One model would be to have an umbrella organization that started with a handful of individual roadmaps that generate a sufficient level of interest in industry and academia (perhaps based on membership fees) to initiate and sustain this activity. A resulting roadmap and associated data could be shared among the membership of that particular roadmap. If these efforts proved effective, additional roadmaps could be instigated and others terminated as appropriate based on level of interest. Such roadmaps would be useful not only to the researchers and product developers, but also to government agencies to decide where programs would effectively fill gaps and enable desired products and applications. Private investors could also become members of these roadmaps and use the data to decide where their investments would be successful.

2.3 Engaging Federal Agencies: The program committee felt that federal agencies such as NSF, DARPA, ONR, AFOSR, NIH and DOE should be engaged directly in the ENRI efforts. ENRI-2013 was partly funded by NSF, however (due largely to federal sequestration of travel) no program managers from NSF and DARPA attended ENRI. Two specific approaches to engage the federal agencies are discussed below.

2.3.1 Guidance for Nanomanufacturing Proposal Review: The participants identified the following guidelines that could make federally supported nanomanufacturing research more effective[1]:

- When formulating calls for and evaluating nanomanufacturing and related proposals consider not only the proposed basic process, but also consider the precision controllability of the tools/process over long range and its potential for scalability.
- Encourage proposers to include a rigorous analysis of competitive techniques by comparing metrics related to process performance/cost, tool reliability, and process yields. The research should also identify any gaps in the required metrology and characterization tools.
- Include more industry participation in peer review panels.
- Enable companies trying to develop new nanotechnology products by creating regional centers *via* programs such as the NNMI and make the NSF NNIN, NSEC and ERC centers more effective by reducing barriers to their use by companies.
- Fund the development of new fabrication and metrology tools for nanomanufacturing (via the NSF MRI and other programs). Include in proposal evaluation the plans to make these tools widely and frequently utilized.

2.3.2 Engaging Federally Funded Centers in the Road-mapping Activities: The participants also felt that federally funded centers related to nano-scale manufacturing processes such as NSF NSECs and NERCs, DOE EFRCs, etc. should be encouraged to participate in ENRI, and engage in road-mapping activities that are relevant to their specific focus areas. ENRI-2013 attendees included the leaderships teams of 3 recently funded NERCs (NASCENT led by UT-Austin, ASSIST led by NCSU and

[1] The workshop organizing committee felt that some of these recommendations may already be in place at some of the federal agencies. However, these recommendations have been included here for the sake of completion.

TANMS led by UCLA), and two NSECs (Nano-CEMMS at Illinois and CHM at UMass-Amherst). If a common road-mapping framework can be developed by ENRI in collaboration with the leadership of such centers, this framework can be proposed for use by these and other centers in the area of nanomanufacturing. This could potentially lead to a standardized approach for meaningful two-way exchange between research and educational efforts of such centers and industry at large.

3. Workshop responses to the three questions for the NSF:

3.1 **National Security Issues:** The workshop participants acknowledged the important role that the agencies of the DoD and other federal entities have played in funding research that is intended to develop nanotechnology applications that affect national security. However, this necessarily imposes restrictions on research and development of these applications that are counterproductive to innovation.

In a broader sense, the workshop participants concluded that our national security depends on a thriving and innovative economy. It is well established that innovation requires close contact with manufacturing methods and that the loss of cutting edge manufacturing techniques impairs the ability to innovate.

3.2 **Learning from market failures**: Innovation always incurs risks and market failures large and small are inevitable. However, there are well established approaches that can mitigate these risks and improve chances of market success. While financial capital is undoubtedly important, the knowledge of how to expend that capital is also key. There are numerous examples of very well-funded nanotechnology firms that have nevertheless failed. A detailed analysis of each failure is beyond the scope of the workshop; however, arguably many of the failures involved not fully understanding the technical barriers to manufacturing and/or not enough information about the intended market. Our suggested road-mapping activities could provide this sort of information that could dramatically improve the effectiveness of expending what financial capital is available and enhance the chances of success.

3.3 **Risk of doing nothing to enable rapid nanofabrication innovation:** It has been argued that the existing digital manufacturing fabrication infrastructure has more than enough flexibility to allow for rapid innovation by simply being clever about how to exploit this marvelous system, and that improved computer aided design will yield the new applications that will drive our economy. Indeed, the path of homogeneous integration into the semiconducting manufacturing juggernaut is one that has proven to be extremely fruitful.

However, there are well documented examples of how a well-established manufacturing approach is derailed by a novel fabrication approach (The Innovator’s Dilemma). Novel fabrication and metrology approaches are generated continuously for the IC industry because of well-established economic engine that it is and the extensive efforts of road-mapping to reduce uncertainty. However, for non-IC products, new tools and methods must also continue to evolve if innovation is to proceed as it must for our nation's economic well-being. If Deep Reactive Ion Etching and various release technologies were not developed, we would not have many of the MEMS products that are now a staple of automotive, aerospace, personal electronics, etc. Continually placing tools in the tool box is the only way to continue innovation. If we fail to do this we may reap the fruits of previous investments in fabrication technology for a while, but we will eventually stagnate and fail.

We must create a superior environment that enables rapid innovation and enlarges the ecosystem for nanomanufacturing. This was done with spectacular success with the semiconductor industry. We can do the same for nanomanufacturing.

4. Next Steps:

There was a strong sentiment from several of the organizers and participants that there should be a follow-on ENRI workshop to continue the efforts started in ENRI-2013 and to follow-up on the key recommendations presented in Section 2. ENRI-2013 program had the following basic components:

(i) Plenary and invited speakers that addressed federal policy in advanced micro- and nano-scale manufacturing; presented case studies of successful technology transfer in nanomanufacturing in areas such as electronics and biotechnology; and innovative technologies in academia and industry (including small companies) that could lead to rapid innovation.

(ii) Three sets of round table discussions that were based on basic guidelines provided by the workshop organizing committee with the goal of identifying promising nano-scale fabrication technologies for rapid innovation in emerging device sectors.

(iii) Two poster sessions (preceded by a rapid fire poster summary presentations) to facilitate technical exchange between the various participants from academia, national labs and industry; and to allow students and post-doctoral researchers from academia and national labs to interact with researchers and technology leaders in the field.

The workshop organizing committee has prepared the attached questionnaire that it will be sending to ENRI-2013 participants to see how the workshop benefited the participants, and how we could refine the workshop scope in the coming years year to benefit the participants.

Opportunities details:

KEYS TO RAPID INNOVATION:

- **Compress nanodevice design/test cycle – maskless lithography, novel material integration are keys**
  - As rapid innovation is the key to successful nanodevice applications it is essential that prototypes be produced with short cycle times so that the design/test cycle can be exploited quickly. The workshop participants pointed to a gap in the ability to do maskless lithography and novel material integration.

- **Wikifab, network of manufacturing capabilities**
  - Across the country there are many fine micro and nano fabrication facilities, and while the NNIN has made efforts to make their network more transparent and easy to access, the workshop participants believed that developing an internet based software application that did not only list available processes within process facilities, but actively suggested one or more feasible process flows to fabricate a particular device or system. The potential process flows which would span one or more processing facility should include an estimation of timing and costs for the prototyping and/or manufacturing of the nanodevice/system.

- **Regional, flexible pilot production facilities**
  - There are a substantial number of user facilities at the NNIN, other university labs, and at National Labs that support development of nanotechnology products and applications. However, many of these user facilities do not support production. A huge boost to rapid innovation would be regional, flexible pilot production facilities. Road-mapping the needs in a given region would help a production facility specialize and better meet its customer base's needs.

- **Addressing legal barriers for academia, industry, government collaboration**
  - There are legal barriers to having academia, industry, and government entities collaborate effectively that could be addressed by the government. These should be reassessed and reduced or eliminated if careful assessment concludes the benefits outweigh the risks of the change. However, there are also quasi legal barriers as well that do not require government action to reduce. One area that has hampered industry – university interactions is the insistence that the intellectual property must remain with the university and that industry must pay a royalty to access the rights to use patented inventions that they paid for the research that led to the invention. While there are some legal issues such as the Bayh Dole Act about ownership of IP generated with federally funded research, there is ample latitude to universities to provide nominal or no cost licensing to industrial funders of research.

- **Open source set of tools**
    - As novel devices/systems are invented, novel processing is often required. Workshop participants thought that one potential solution is a set of “open source” tools would be a major advantage. While this approach is principally used in the software tool regime, it is thought that a similar approach which would allow a community to share the advances in fabrication / metrology tools would allow rapid innovation in both tools and products to flourish.

- **Simplified manufacturing processes – Lowering the mask count**
    - The most expensive component of manufacturing a specific nano or micro scale product is often the masks required to manufacture the product. The dream solution is to eliminate the need for masks entirely with cost effective maskless lithography, but an alternative is to create processes that reduce the number of masks required.

- **Massive integration of electronics with rapid 3D prototyping**
    - While the semiconductor juggernaut is not the direct concern of the workshop, many innovative nanotechnology products will exploit VLSI and the integration of electronics by standard means, printed circuit boards for instance, is often not consistent with the desired product specifications (size, weight, etc.). A process that allowed integration with rapid 3D prototyping is an attractive proposition.

- **Integrating nano-materials with existing processes (e.g. nanotubes in VLSI)**
    - The other side of the coin for integration of VLSI and nanoproducts is the integration of nano-materials (nanotubes, graphene, quantum dots, etc.) into VLSI or other advanced manufacturing processing. Providing paths to introducing nano materials into VLSI processing is viewed as a very promising opportunity.

- **CAD tools to enable DNA, RNA self-assembly nanomanufacturing**
    - The ability to synthesize DNA with a specified coding of bases has led to a remarkable ability to produce two and three dimensional nanostructures. A subset of these DNA structures have already proven useful. A CAD tool that permitted DNA and RNA programmed assembly to create designed structures could very positively affect the ability to rapidly innovate nanoscale applications and products.

SPECIFIC MANUFACTURING TECHNOLOGIES

- **Continuous roll to roll nano-scale printing processes**
    - This technology is seen as an extremely cost effective nano-manufacturing process that escapes the batch processing mode that is the rule in most micro and nano manufacturing processes. While there is currently a non-trivial amount of support for developing roll to roll

nanoscale printing, the potential impact is so large that additional investment into this technology would seem to be warranted. The ability to align patterns accurately is a particularly important capability.

- **Additive/3D manufacturing at the micro and nano scale.**
    - Additive / 3D manufacturing is a particularly attractive approach to enabling rapid innovation. There is at least one tool on the market from Nanoscribe that has a 3D printer with 150nm resolution and has demonstrated nanoscale (<100nm) 3D printing. However, materials are still fairly limited and processes for this and hopefully soon to emerge other tools have yet to be exploited for manufacturing. Significant opportunities present themselves for rapid prototyping and small lot manufacturing if improved processes can be developed.

- **Inkjet printing: additive and direct write**
    - Inkjet technology has been a huge success in printing and the workshop participants believe that there are significant opportunities both for direct write patterning and additive manufacturing processes.

- **Layer by layer processing (e.g. ALD) in roll to roll and other nanomanufacturing**
    - Atomic Layer Deposition (ALD) and other layer by layer processes (etching) are a powerful and relatively inexpensive method of achieving excellent resolution in deposition and etching that complement patterning processes. However, they currently lag patterning technique development in roll to roll processing.

- **Atomically (and absolutely) precise manufacturing with top down control**
    - Improved manufacturing precision has a well-established track record for producing higher quality, more efficient, longer lasting products, and in the long run reduces manufacturing costs. However, as precisions approach the molecular and atomic scale, the granularity of materials presents problems and opportunities. The opportunities include developing digital fabrication techniques that add or remove matter in discrete atoms or molecules and ideally uses the quantized nature of matter as a guide and address grid. Digital processes will lead to more accurate fabrication and should allow atomic precision which can be exploited for a number of promising applications. Digital matter would be possible when precision is absolute (in terms of the number and position of atoms). Digital matter could supplant analog matter in the same way digital electronics has supplanted analog electronics in many many applications.

- **Rapid and inexpensive fabrication of nanoimprint templates**
    - Nanoimprint is a very cost effective method of patterning at the nanoscale, but writing templates is a costly and time consuming process.

An attractive target that would enable rapid innovation is short turnaround time and inexpensive production of nanoimprint templates.

- **Nano-materials synthesis: Pharma/bio, feedstock for other tools/processes**
    - o Nano materials can be the building blocks for a wide variety of innovative nano products. However, the quality control for purity, shape, size, etc. are often not achieved in the manner that allows their integration into potentially important applications.

- **High throughput e-beam/optical lithography (e.g. for DoD needs)**
    - o For short run production of specialized products such as those custom chips required by the DoD there is a need for flexible yet reasonably high throughput patterning systems that could perhaps be provided by mix and match between e-beam and optical lithography.

- **Alternative patterning: Ion/e-beam, radioisotope lithography nanopatterning**
    - o Mainstream semiconductor lithography tools have become astronomically expensive to purchase and maintain, and even then demand large production runs to support the costs of the masks. E-beam lithography tools have been the primary nanolithography tool for researchers and developers and are made available to developers through various channels such as the NNIN and other user facilities in universities and national labs. However, transition to manufacturing is difficult as many of the facilities do not support manufacturing and e-beam tools are expensive and have low throughputs. Development of alternative nanopatterning techniques that are suitable for manufacturing products other than commodity integrated circuits should be supported.

- **Interference lithography for periodic structures**
    - o Interference lithography was called out as an attractive technology for producing micro and nanoscale periodic structures which are useful for many manufacturing processes.

- **Better 3D metrology tools for MEMS/NEMS**
    - o While the situation is improving, the workshop participants felt that there were still many unmet needs in 3D metrology for MEMS and NEMS products.

- **Closed loop metrology in nanofabrication – chip-scaled SPMs**
    - o Chip scale scanning probe microscopes (SPMs) could dramatically improve resolution and, through parallelism, the throughput of metrology tools used for nanomanufacturing. A CMOS MEMS approach makes the development of the chip scale SPMs more tractable and their manufacturing more affordable. This approach also allows these SPMs to

be smart SPMs by including a microcontroller that could dramatically reduce integration difficulties for arrayed SPMs by allowing the smart SPMs to be placed on a digital bus so that high level instructions and results could be transmitted digitally on the bus.

- **Inline metrology (<50nm)-real time -next step process variations**
  - Metrology is at the heart of manufacturing and deserves more attention than it is currently receiving. Since metrology tools that operate at the nanoscale are difficult to make universal, there is an obvious chicken and egg problem of what specifications to develop a metrology tool to. This is another area where a road-mapping activity could identify where there are needs and reduce the risk of developing metrology tools that would support nanomanufacturing.

- **Atomic GPS: atomic scale positioning over entire wafer**
  - A metrology system that allowed atomic scale accuracy in positioning over an entire wafer in X, Y, and Z would impact many nanofabrication tools and processes.

- **Small vacuum pumps and systems, enabling small instruments**
  - Microfabrication technology has produced many highly miniaturized systems with excellent capabilities such as mass spectrometers, electron optical systems, ion optical systems, and others that require vacuum environments. Commercialization of these systems has often been severely hampered by lack of miniaturized vacuum systems. While there was at least one DARPA program on this subject, the workshop participants believed that further support for miniaturized vacuum pumps and systems would be a wise investment.

- **Intelligent biosensors (wearable) especially packaging and material integration**
  - There are many efforts, including a new NSF ERC, to explore wearable biosensors that could greatly improve the collection of medically relevant information for research or to influence effective therapy for patients. Both packaging and heterogeneous material integration were highlighted as critical areas that hamper rapid innovation. However, there are other significant barriers. Researchers and developers who are attempting to create useful applications and products have little idea what the medical industry would find acceptable. In other words, the specifications for the biosensor products are unknown. If specifications acceptable to the medical community could be established, this would dramatically aid rapid innovation.

- **Etching magnetic materials**
  - Bit patterned media is one, but not the only application that would benefit significantly from a high resolution (dry) etch process for magnetic materials. Ion milling is currently the technology of choice but it has serious limitations. One new dry etch technology presented at the workshop, Low Energy Electron Enhanced Etching (LE4) presented by Pat Gillis of Systine has not demonstrated etching of magnetic materials, but this possibility could be explored.

WORKSHOP AT A GLANCE

Sunday, August 18

18:00 - 20:00	WELCOME RECEPTION & REGISTRATION

Monday, August 19

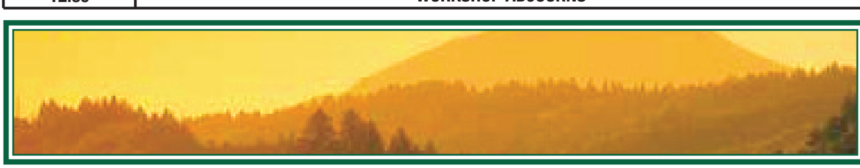
07:30 - 11:00	REGISTRATION
08:30 - 09:00	OPENING WELCOME **Workshop Chairs:** S.V. Sreenivasan & David S. Ricketts
09:00 - 10:00	PLENARY I Dr. Thomas R. Kurfess, *Georgia Institute of Technology, USA*
10:00 - 10:30	SHOTGUN ORAL POSTER SESSION A
10:30 - 11:45	POSTER SESSION A & Break
11:45 - 13:00	Lunch
13:00 - 13:45	INVITED SPEAKER I Dr. Stephen W. Turner, *Pacific Biosciences, USA*
13:45 - 14:30	INVITED SPEAKER II Dr. Martin A. Schmidt, *Massachusetts Institute of Technology, USA*
14:30 - 14:45	Break
14:45 - 17:30	ROUNDTABLE DISCUSSION TOPIC I Opportunities for Rapid Innovation

Tuesday, August 20

08:45 - 09:00	OPENING REMARKS - John Randall
09:00 - 10:00	PLENARY SPEAKER II Dr. C. Mark Melliar-Smith, *Molecular Imprints, Inc., USA*
10:00 - 10:30	SHOTGUN ORAL POSTER SESSION B
10:30 - 11:45	POSTER SESSION B & Break
11:45 - 13:00	Lunch & BEST POSTER AWARD
13:00 - 13:45	INVITED SPEAKER III Dr. Thomas R. Albrecht, *Hitachi Global Storage Technologies, Inc. (HGST), USA*
13:45 - 14:30	INVITED SPEAKER IV Dr. David L. Trumper, *Massachusetts Institute of Technology, USA*
14:30 - 14:45	Break
14:45 - 17:30	ROUNDTABLE DISCUSSION TOPIC II Tools/ Access Needed for Rapid Innovation for Opportunities Identified on Monday
18:00	WORKSHOP BANQUET

Wednesday, August 21

08:15 - 08:30	OPENING REMARKS
08:30 - 09:30	PLENARY SPEAKER III Benjamin N. Eldridge, *FormFactor, Inc.USA*
09:30 - 10:15	INVITED SPEAKER V Dr. Michael Walsh, *LumArray, Inc., USA*
10:15 - 11:00	INVITED SPEAKER VI Dr. H. Pat Gillis, *Systine, Inc., USA*
11:00 - 11:15	Break
11:15 - 12:30	ROUNDTABLE DISCUSSION TOPIC III Call to Action - Recommendations to Enable Nanofabrication for Rapid Innovation
12:30	WORKSHOP ADJOURNS



ENABLING NANOFABRICATION FOR RAPID INNOVATION

Monday, August 19

To assist you with finding the paper in the Digest, we have provided the page number following each paper title.

08:30 **OPENING WELCOME**
Workshop Co-Chairs:
David Ricketts, *North Carolina State University, USA*
S.V. Sreenivasan, *University of Texas, Austin, USA*

09:00 **PLENARY SPEAKER I**
Session Chair: T. Kenny, *Stanford University, USA*

10:00 **SHOTGUN ORAL POSTER SESSION A**
Session Chair: J. Randall, *Zyvex Labs, USA*

10:30 **POSTER SESSION A & BREAK**

Transformative Fabrication Techniques for Rapid Innovation

John N. Randall, Zyvex Labs

John N. Randall, Zyvex Labs

Nano-Precision Instruments and Metrology

ENABLING NANOFABRICATION FOR RAPID INNOVATION

Tuesday, August 20

Top-Down Nanomanufacturing

Directed Nanomanufacturing

Nano-Precision Instruments and Metrology

Late News

11:45 **Lunch & BEST POSTER AWARD**

13:00 **INVITED SPEAKER III**
Session Chair: R. Bonnecaze, *University of Texas, Austin, USA*

13:45 **INVITED SPEAKER IV**
Session Chair: A. Linden, *Raith USA, Inc., USA*

14:30 **Break**

14:45 **ROUNDTABLE DISCUSSION TOPIC II**
Tools/Access Needed for Rapid Innovation for Opportunities Identified on Monday
Session Chair: S.V. Sreenivasan, *University of Texas, Austin, USA*

18:00 **RECEPTION**
18:45 **DINNER**

John N. Randall, Zyvex Labs

ENABLING NANOFABRICATION FOR RAPID INNOVATION

Wednesday, August 21

08:30 PLENARY SPEAKER III
Session Chair: S.V. Sreenivasan, *University of Texas, Austin, USA*

09:30 INVITED SPEAKER V
Session Chair: G. Skidmore, *DRS Technologies, USA*

10:15 INVITED SPEAKER VI
Session Chair: N. Sarkar, *University of Waterloo, CANADA*

11:00 **Break**

11:15 ROUNDTABLE DISCUSSION TOPIC III
Call to Action - Recommendations to Enable Nanofabrication for Rapid Innovation
Session Chair: D. Ricketts, *North Carolina State University, USA*

12:30 **WORKSHOP ADJOURNS**

ENABLING NANOFABRICATION FOR RAPID INNOVATION

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Enabling Nanofabrication for Rapid Innovation

August 18 – 21, 2013

Silverado Resort and Spa
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