Emerging Research Materials and Processes

Center For Hierarchical Manufacturing - National Nanomanufacturing Network: Nanomanufacturing Systems Workshop

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Overview

- Background and motivation
- Nanomanufacturing research priorities
  - Overview
  - Selected strategic research opportunities
- Key messages
Adding value through functional scaling on CMOS: Dimensional scaling + integration of functional materials

Functional Diversification

- Analog/RF
- Passives
- HV Power
- Sensors, Actuators
- Biochips

Goals: Sense, Power, Process, Interact, Empower

ITRS

2005 edition

Non-digital content System-in-package (SiP)

Combining SoC and SiP: Higher Value Systems

Information Processing

Digital content System-on-chip (SoC)

Interacting with people and environment

Beyond CMOS
Rising Cost of Wafer Fabs Vs. GNPs

GNP of:
- Denmark
- Singapore
- Hungary
- Czech Rep.
- Luxemburg
- Guatemala
- Panama
- Kenya
- Macedonia
- Monaco

Ralph Dammel  SPIE 2002
Difficult Material Scaling Challenges

- **Line-edge Roughness**

- **Long-Range Dimensional Control and Repeatability**

- **Pattern Fidelity**

- **Resolution: Catalytic Blurring**
## Nanomanufacturing Research Priorities

### Patterning

1. **Directed Self-Assembly**
   - 1.1 Directed Self-Assembly
   - 1.2 Nanoimprint Patterning
   - 1.3 Post NGL Patterning
2. **Manufacturing for Design**
   - 1.4 Manufacturing for Design
   - 1.5 NGL Extensibility/Limits
   - 1.6 Low-Volume Patterning

### Nanoengineered/Emerging Materials

1. **ITRS Identified Emerging Research Materials**
2. **Functional Diversification and Heterogeneous Integration on CMOS**
3. **Low-Temperature Materials and Processes**
4. **Materials by Design**
5. **Deterministic Fabrication**

### Environment, Safety, Health

1. **Water and Energy**
2. **Design for ESH**
3. **Additive/Wasteless Processes**
4. **ESH Impact of New and Nanomaterials for CMOS**
5. **Sustainable Chemical Substitution**
6. **Hierarchical Assessment**

### Nanocharacterization/Metrology/Modeling

1. **Limits of Known Characterization Methods**
2. **Nanoscale Defects, Visual, and Non-Visual**
3. **Breakthrough Methods; e.g. In-situ 3D Imaging of Atomic and Nanoscale Materials**
4. **Metrology for MFD and DFM**
5. **Measuring Coupled Nanoscale Phenomena**
6. **Nanoscale Probe-Sample Measurement Uncertainty**
## Directed self-assembly: Can it extend nanomanufacturing?

### 2012 ITRS Emerging Research Material Requirements: Self Assembling Materials

<table>
<thead>
<tr>
<th>Metric</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defects</td>
<td>&lt;0.02 20 nm defects cm(^{-2}) [Develop a basic understanding of material and process defect related mechanisms; Develop strategies to achieve projected ITRS requirements]</td>
</tr>
<tr>
<td>Low Frequency LER</td>
<td>~2.1 nm 3(\sigma)</td>
</tr>
<tr>
<td>Gate CD Control</td>
<td>~1.7 nm 3(\sigma)</td>
</tr>
<tr>
<td>Resolution</td>
<td>11 nm</td>
</tr>
<tr>
<td>Essential shapes</td>
<td>Dense and isolated L/S, circles, hexagonal arrays</td>
</tr>
<tr>
<td>Overlay and registration</td>
<td>5.1-7.1 nm 3(\sigma)</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>1 W/ Min [Via single wafer or batch processing]</td>
</tr>
<tr>
<td>Etch and pattern transfer</td>
<td>Satisfy projected ITRS requirements for patterning electronically useful features</td>
</tr>
<tr>
<td>Placement and orientation</td>
<td>20% of the critical dimension</td>
</tr>
<tr>
<td>Multiple Sizes-Pitches/ Layer</td>
<td>2-3/ layer</td>
</tr>
<tr>
<td>Ease of integration</td>
<td>Compatible with CMOS processing</td>
</tr>
<tr>
<td>Overall Performance</td>
<td>Competitive with chemically amplified resist processing</td>
</tr>
<tr>
<td>Other</td>
<td>ESH impact requirements? Functional diversification applications?</td>
</tr>
</tbody>
</table>

Addressed by SRC’s Research Team
Essential Features for Integrated Circuits

- Periodic Spots
- Isolated Spot
- T Junctions
- Isolated Line
- Periodic Lines
- Bends
- Jog
**Comparison of Subtractive Versus Bio-assisted Self-Assembly/Patterning**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits patterned per second</td>
<td>~ 8.59E+09 bits/ s/ masking layer</td>
<td>7.53E+17 amino acid equivalents/ s</td>
<td>~ 9E+07</td>
</tr>
<tr>
<td>Energy required per bit</td>
<td>&gt; 1.46E-12 J/ bit/ masking layer</td>
<td>1.29E-20 J/ amino acid equivalent [4.57 KTLn(2)]</td>
<td>&gt; 1E+8</td>
</tr>
</tbody>
</table>

Consider leveraging natural processes.
Manufacturing for Design: Technology - Design Interdependencies

Circle of Innovation

Global Optimization of: Variability, Performance, Matching, Centering, Reliability, Cost, & Sustainability

- Applications
- Materials
- Processes
- Devices
- Circuits
- Systems
- Architectures
- Regular Fabrics

Design for Manufacturing

Application Specific Materials

Directed Assembly

Manufacturing for Design
Nanoengineered Materials: Macromolecular Scale Devices are on the ITRS Horizon

Macromolecular Scale Components:
- Low dimensional nanomaterials
- Macromolecules
- Directed self-assembly
- Complex metal oxides
- Hetero-structures and interfaces
- Spin materials
- Benign and sustainable nanomaterials

Emerging Research Materials

Functional Diversification: Information and Energy Management

Distributed intelligent networks of autonomous systems composed at the nano-level with adaptive emergent behaviors;

H2 Fuel Cell Powered, Nanotube Composite Aircraft

High Altitude Long Endurance Remotely Operated Aircraft
Functional Diversification:
Sensing—thermal, chemical, mechanical

Thermal and odor (?) via thermal expansion

Odor (e.g., sex) via protein gating

Vibration and odor via hair arrays and shaft-like mechanical motion

Melanophila acuminata beetles

Schmitz, Nature 1997, 386, 773

Odor sensing proteins in the antennae of moth, Lymantria dispar.


Cupiennius salei Keys spider

Barth, A Spider’s World: Senses and Behavior. 2002
Functional Diversification: Prototypical Semiconductor Bioelectronics Roadmap

**Research Goal**

- 2D arrays of pressure sensors with sub10 μm resolution
- On-chip integrated energy sources
- A two-way interface between neurons and transistors
- Bio-FET
- Sensing state of individual cell
- e.g. artificial eye

**Application**

- Tablet PC
- Clinical Assistant
- High-resolution tactile imaging for palpation
- Implantable microsystems

**Biomimetic material architecture, nanofabrication, and function**

- 2007
- 2xxx
No firing with catalyzed growth process!

G. Ahmad, M. B. Dickerson, B. C. Church, Y. Cai, S. E. Jones, R. R. Naik, J. S. King, C. J. Summers, N. Kroger, K. H. Sandhage, 
Ex. Droplet on Demand patterning enables low temperature [130°C] Cu sintering and enhanced conductivity.

V. Subramanian and J. Bokor

What is the ESH impact of 5 nm Cu particles?
The catalysis rate of ethylene to vinyl acetate is a function of the atomic spacing between Pd atoms in the Pd-Au matrix.

What is the correlation between the atomic structure of a surface or catalyst and thin film growth or CNT helicity?
Example. Zinc oxide

Why does zinc oxide express different shapes and different physicochemical properties, with the same zinc oxide composition?

Wang et al., Materials Today, 2002
Deterministic Fabrication:
Goal - Reduce device variability

ITRS Trend for the Number of Channel Electrons

- Conductance variability reduced from 63% to 13% by controlling dopant numbers and roughly ordered arrays;
- Conductance due to implant positional variability within circular implant regions of the ordered array ~ 13%.

[Waseda University]
Deterministic fabrication: Continued

a) STM image of In nanoclusters on Si(111) at an In coverage of ~0.05 monolayers [Ref.: Li, et. Al., Physical Review Letters, 88, 66101 (2002);]


The convergence of today’s difficult challenges, emerging market drivers, and recent breakthroughs in materials technology represents a rare opportunity for chemists, chemical engineers, materials scientists, and others to develop breakthrough material and process insertion options;

This is a good time for the research and development communities to question some of our basic assumptions.

Must the percent variability, with respect to projected application and architecture requirements, increase with functional density?

Do emerging materials and processes exist that could enable new and more favorable cost curves for nanoelectronics fabrication?

With respect to functional diversification, is it possible to design custom nanomaterials with electronically useful, application specific functionality?

However, it remains to be seen whether potential material and process solutions are identified and matured in time to impact key insertion windows.
Discover phase ~20 yrs; Innovation phase ~12 yrs.

Example: Solid State Rectifier

<table>
<thead>
<tr>
<th>Technology</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>Learning Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State Diode</td>
<td>26</td>
<td>7</td>
<td>6</td>
<td>13 years</td>
</tr>
<tr>
<td>Vacuum Tube</td>
<td>20</td>
<td>9</td>
<td>6</td>
<td>15 years</td>
</tr>
<tr>
<td>Transistor</td>
<td>25</td>
<td>6</td>
<td>5</td>
<td>11 years</td>
</tr>
<tr>
<td>Integrated Circuit</td>
<td>17</td>
<td>3</td>
<td>5</td>
<td>8 years</td>
</tr>
</tbody>
</table>

V. Zhirnov/ SRC
Thank you