The Development of the Semiconductor CVD and ALD Requirement
1. We create knowledge and develop unique insights at the intersection of electronic thin film processes and the chemicals industry

2. We help our clients to succeed through our:
   • Experience in global electronics and advanced materials and thin film processing industries:
     - Semi
     - Packaging
     - Nano Technology
     - LCD
     - PV
     - Other
   • Experience in the global chemicals industry
   • Experience at Device Producers
   • Experience at OEMs
   • Global network and capabilities
   • Advanced modeling capabilities
## High Confidence Decision Support Services

### PLANNING
- Business Analysis
- M&A / Due Diligence
- Diversification / Expansion Planning

### IDEAS TO MARKET
- IP Development
- Value Chain Analysis
- Technology Assessment and Commercialization

### OPERATIONS
- Cost Benchmarking
- Competitive Intelligence
- COO Models and Assessment
- Process Technology Assessment

### MARKETING & SALES
- Market Analysis/Monitoring
- Market Forecasting and Modeling
- Competitive Intelligence
- Customer Perceptions

### SINGLE CLIENT SERVICES
Industry Analysis Reports Offered

- CMP Technologies and Markets
- Advanced Thin Films for FEOL and BEOL Applications
- Emerging Materials Opportunities for Advanced Semiconductor Devices
- Advanced Cleaning and Surface Preparation: Technologies and Markets
- Advanced Patterning Forecasting
- Semiconductor Industry Direct Consumables Model
- Advanced Materials and Chemicals for Photovoltaic Cells and Modules
Agenda

• Materials Market Landscape
  • The Semiconductor Device Roadmap
  • Deposition Materials
  • Who Is Doing What?

• The Future
New Industry Structure, 2014

Business model changes required / desirable?

The new “Silicon Valley”

Materials innovations required

Notes:
1. Bottom axis is on a percentage basis
2. Size of box is proportional to # wafer starts
3. Source: Semico and Linx estimates
Further Evolution in 2018

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1. Bottom axis is on a percentage basis
2. Size of box is proportional to # wafer starts
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- **The Semiconductor Device Roadmap**
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Logic Device Roadmap

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Node</td>
<td>32/28</td>
<td>22/20</td>
<td>15/14</td>
<td>11</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
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<tr>
<td>Integration Options</td>
<td>Planar</td>
<td>FDSOI</td>
<td>MG</td>
<td>MG</td>
<td>MG</td>
<td>MG</td>
<td>MG</td>
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<tr>
<td></td>
<td>FDSOI</td>
<td>MG</td>
<td>FDSOI</td>
<td></td>
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</tr>
</tbody>
</table>

- III-V likely to replace channel material in later MG devices
- TFET can be Si for first generation and then transfer to alternative materials for second generation
Proposed Logic

Device scaling roadmap

Performance (power x delay)

- Gate oxide
- Buried oxide
- Wsi
- Lg
- Drain
- Gate
- Source
- Ge/III-V, VFET, TFET, NW, Graphene...
- Tunnel FET
- Graphene
- nanowires
- FinFET
- Gate-first
- Gate-last
- 32-22/20
  - High-k, Metal Gate
- 22/20-15
  - Multi-gate
- 90-65-45
  - Strain, USJ (F,C co-implant, ...)
- 11-7

Ultra-thin body with RSD

Benefits
- Extension of planar technology (less disruptive to manufacturing)
- Improved RDF (low doped channel)
- Excellent channel control
- Potential for body bias

Sources: IMEC, Intel
## NAND Flash Roadmap

<table>
<thead>
<tr>
<th>Category</th>
<th>2010 - 2015</th>
<th>2016 - 2020</th>
<th>2021 - 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAND</td>
<td>MLC</td>
<td>MLC 3D</td>
<td>MLC 3D TSV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MLC 3D TSV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Next Gen 3D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Next Gen 3D TSV</td>
</tr>
</tbody>
</table>
Implementation of 3-D

3D NAND Flash Schemes

- Toshiba: P-BICS (perpendicular cell string)
- Samsung: BICS (perpendicular cell string), TCAT (perpendicular cell string), VG-NAND (horizontal cell string)

Year paper presented:
- 2006: S³ (horizontal cell string)
- 2007: BICS (perpendicular cell string)
- 2008: TCAT (perpendicular cell string)
- 2009: VG-NAND (horizontal cell string)
# DRAM Scenarios

<table>
<thead>
<tr>
<th>Category</th>
<th>2010 - 2015</th>
<th>2016 - 2020</th>
<th>2021 - 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM Best Guess</td>
<td>DRAM</td>
<td>DRAM and TSV</td>
<td>Next Gen</td>
</tr>
<tr>
<td>DRAM runs late</td>
<td>DRAM</td>
<td>DRAM and TSV</td>
<td>Next Gen</td>
</tr>
<tr>
<td>Replacement Technology comes</td>
<td>DRAM</td>
<td>DRAM and TSV</td>
<td>Next Gen 3D or TSV</td>
</tr>
<tr>
<td>early</td>
<td></td>
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</tr>
</tbody>
</table>
Agenda

- Materials Market Landscape
- The Semiconductor Device Roadmap
- **Deposition Materials**
- Who Is Doing What?

- The Future
# Precursor Families

<table>
<thead>
<tr>
<th>Materials</th>
<th>Applications</th>
</tr>
</thead>
</table>
| Chlorosilanes and DCDS | • Used for Si epi  
                          • Used to produce compressive and tensile stress films for planar logic devices                                                    |
| Disilane               | • Used as a precursor to grow high quality polysilicon/silicon films. Used in DRAM and NAND today. Will be precursor for high quality polysilicon, replacing some silane |
| Ge and Germane         | • Primarily GeH4. Used in advanced logic (planar) for channel stress and in DRAM as part of the electrode at Samsung and Hynix. Will be used in multi-gate transistor stress as well as compound semiconductor multi-gate structures. Also used in SiGe wafers. Expect MO version to be introduced for lower temperature processing |
| HCDS                   | • Hexachlorodisilane – Used as a spacer in litho for double, triple and quadruple patterning (pitch doubling, etc.). Also used as a sidewall spacer in advanced logic transistor – planar structures. Used as a representative material for all advanced spacers (amino silane types – LTO and SAM) |
| LKD                    | • Represents all low-k dielectrics – methyl silanes                                                                                           |
| PDMAT                  | • Ta precursor that is used in planar HKMG applications as well as TaN in copper barrier seed applications. Likely TA precursor of choice for future applications |
| TDMAT, Ti and TiCl4    | • Next generation Ti precursor, which is currently replacing TiCl4. Can be used in electrodes as well as HKMG applications and in RRAM structures, etc. Ti and TiCl4 are older sources that will grow and see increased competition from TDMAT on lower temperature and performance applications |
| TMA Hf and TEMA Hf     | • Workhorse high-k material used in logic applications as well as RRAM, NAND                                                                 |
| TSA                    | • Trisilylamine. Used on advanced gapfill processes (STI and PMD) in logic and memory starting at 32 nm. Can replace polysilozane PMD                                                |
| TMA/ZAZ and ZAZ        | • Zr materials are used mostly for current generation of HK capacitors                                                                     |
Market For Advanced Thin Films ($M)

CVD and Epi

<table>
<thead>
<tr>
<th>Year</th>
<th>LKD</th>
<th>FCVD eHARP</th>
<th>Strain nitride</th>
<th>Germane</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
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<tr>
<td>2011</td>
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<tr>
<td>2012</td>
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</table>
Market For Advanced Thin Films ($M)

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK CAP</td>
<td>HKGD</td>
<td>MG</td>
<td>Nucleat.</td>
<td>Spacer</td>
<td>Litho Spacer</td>
</tr>
</tbody>
</table>

ALD
Agenda

• Materials Market Landscape
• The Semiconductor Device Roadmap
• Materials For Lithography
• The Lithography Decision Chain
• **Who Is Doing What?**

• The Future
Materials Market

- Process complexity is driving higher growth in materials demand than the wafer start growth
  - The BOM component of semiconductor sales will increase over the next 5 years

- The vapor precursor segment outgrows all other segments dramatically
Leading Suppliers, 2010

- Nikko
- Praxair
- Tosoh
- Honeywell
- AZ
- Voltaix
- ATMI
- APC
- Air Liquide
- ADEKA
- UPChem
- Dow Corning
- Linde
- JSR/TCL
- MLI
- KOJUNDO
- Techno...
- BASF
- SAFC
- DNF
- Dow
- FFEM
- Mitsui
- Nanmat
- UMT
- Other

$0
$50
$100
$150
$200
$250

millions

PVD
SOD
Plating
CVD
ALD
## Opportunity Selection and Relationships with OEMs are Critical to Serve Fewer Customers

<table>
<thead>
<tr>
<th>Process</th>
<th>PVD</th>
<th>ECD</th>
<th>CVD</th>
<th>SOD</th>
<th>ALD</th>
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</thead>
<tbody>
<tr>
<td>Key materials suppliers</td>
<td>Nikko</td>
<td>ATMI</td>
<td>Air Products</td>
<td>AZ Electronic Materials</td>
<td>Air Liquide</td>
</tr>
<tr>
<td></td>
<td>Praxair</td>
<td>DEM</td>
<td>ATMI</td>
<td>Materials</td>
<td>Air Products</td>
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<tr>
<td></td>
<td>Honeywell</td>
<td>BASF</td>
<td>Air Liquide</td>
<td>UP Chem</td>
<td>Adeka</td>
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<tr>
<td></td>
<td>Tosoh</td>
<td>MLI</td>
<td>Linde</td>
<td></td>
<td>Kojundo</td>
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<td></td>
<td>DEM</td>
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<td>SAFC</td>
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<td>Tri Chemical</td>
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<td></td>
<td></td>
<td></td>
<td>UP Chem</td>
</tr>
<tr>
<td>Key OEMS</td>
<td>AMAT</td>
<td>NVLS</td>
<td>AMAT</td>
<td>TEL</td>
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<tr>
<td></td>
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<td>(Semitool)</td>
<td>ASM</td>
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<td>TEL</td>
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<td>NVLS</td>
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<td></td>
<td>TEL</td>
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<tr>
<td>Key applications, 2008</td>
<td>Interconnect</td>
<td>Interconnect</td>
<td>Interconnect – LKD</td>
<td>STI &amp; PMD Gapfill</td>
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<tr>
<td></td>
<td>Barrier and Seed</td>
<td>metal</td>
<td>Low-k Barrier</td>
<td></td>
<td>TEL</td>
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<td></td>
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<td></td>
<td>STI &amp; PMD Gapfill</td>
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<td>Emerging – IPS,</td>
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<td></td>
<td>Genintech, etc.</td>
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<tr>
<td>Key applications, 2014</td>
<td>Interconnect</td>
<td>Interconnect</td>
<td>Interconnect – LKD</td>
<td>STI &amp; PMD Gapfill</td>
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<tr>
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<td>Barrier and Seed</td>
<td>metal</td>
<td>Low-K Barrier</td>
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<td>Capacitors</td>
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<td>Caps</td>
<td>Strain</td>
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<td>STI &amp; PMD Gapfill</td>
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<td>Capacitors</td>
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<td>Litho Spacers</td>
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<td>Spacers (non-litho)</td>
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<td></td>
<td></td>
<td></td>
<td>Barrier/seed</td>
</tr>
<tr>
<td>Major Buying Centers</td>
<td>TSMC</td>
<td>Samsung</td>
<td>Hynix</td>
<td>Toshiba</td>
<td>Micron</td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td>Elpida/Taiwan Memory</td>
<td>Intel</td>
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<td></td>
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<td></td>
<td>IBM</td>
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</tbody>
</table>

www.linx-consulting.com
617.273.8837 • 973.698.2331
## Major Developments after 2015

<table>
<thead>
<tr>
<th>Development</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>450mm Wafers</td>
<td>450mm can have a tremendous impact by limiting the number of new fabs built. However, better cost economics can also expand overall semiconductor market growth.</td>
</tr>
<tr>
<td></td>
<td>Not all suppliers, OEMs and Fabs can invest in this platform. Need to chose development partners carefully.</td>
</tr>
<tr>
<td>New Device Architectures</td>
<td>Both non-planar transistors and new memory technologies will expand opportunities for thin film materials suppliers as well as such related processes as CMP, etch and clean.</td>
</tr>
<tr>
<td>EUV Litho</td>
<td>Can impact photo-ancillaries market, especially spacers used in double patterning.</td>
</tr>
<tr>
<td>Summary</td>
<td>However, as often seen in this industry, developments are often later than initially anticipated. We do not believe that 450, non-planar transistors and EUV will all be commercialized at the same time or half-pitch.</td>
</tr>
</tbody>
</table>
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Future Trends in Semiconductor MO Deposition

- The electronic materials supplier business model is being challenged.
- Consolidation drivers persist, but barriers to exit remain.
- The industry structure is changing, and segmenting further.
- A major growth segment for materials suppliers
- Invention is required to meet new integration schemes
- Collaboration with Customers and OEMs is important
- Precursors that cross multiple applications have long term viability
  - Ta, Ge etc. will be needed in multiple generations
  - Other materials will obsolete with new generations