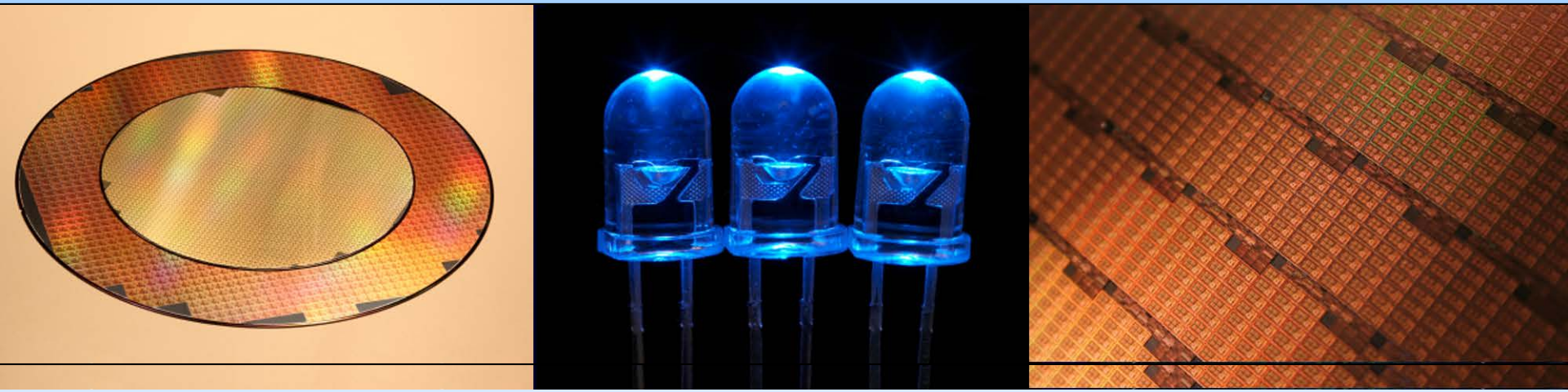

Evolution of CMP and Future Outlook

July 14, 2016

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CMPUG Taiwan Committee Member

LINX Consulting
see beyond the horizon

Agenda

1. Introduction to Linx Consulting
2. Where Have We Been and Where are We Going?
3. Industry Evolution

Introduction to Linx Consulting

Linx Consulting

1. *We help our clients to succeed by creating knowledge and developing unique insights at the intersection of electronic thin film processes and the chemicals industry*

2. *The knowledge is based on a core understanding of the semiconductor device technology; manufacturing processes and roadmaps; and the structural industry dynamics*

3. *This knowledge is leveraged to create advanced models, simulations and real-world forecasts*

4. *Our perspectives are by direct research and leveraging our extensive experience throughout the global industry value chain, including:*
   - Experience in global electronics and advanced materials and thin film processing industries
   - Experience in the global chemicals industry
   - Experience at Device Producers
   - Experience at OEMs

Linx Consulting Service Portfolio

- **Multi-Client Reports**
  - IC Materials
    - CMP
    - Deposition
    - Patterning
    - Cleaning
    - Gases
    - Bulk Chemicals
  - III-Vs, TSV, WLP, Solar

- **Proprietary Projects**
  - Market Planning
  - M & A
  - Growth and Diversification
  - Supply Chain Optimization
  - Technology Commercialization
  - Strategic Planning
  - Voice of the Customer

- **Econometric Semiconductor Forecast**
  - Financial planning
  - Sales and Operational planning
  - Forecasting

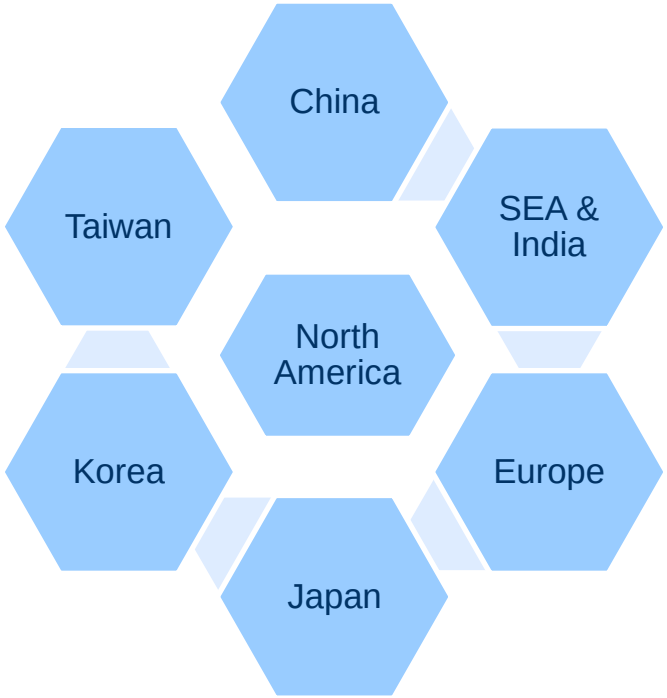
Hilltop Economics LLC

- **Cost Modeling**
  - Client demand modeling
  - Product development
  - Bill of Materials quantification

IC Knowledge, LLC

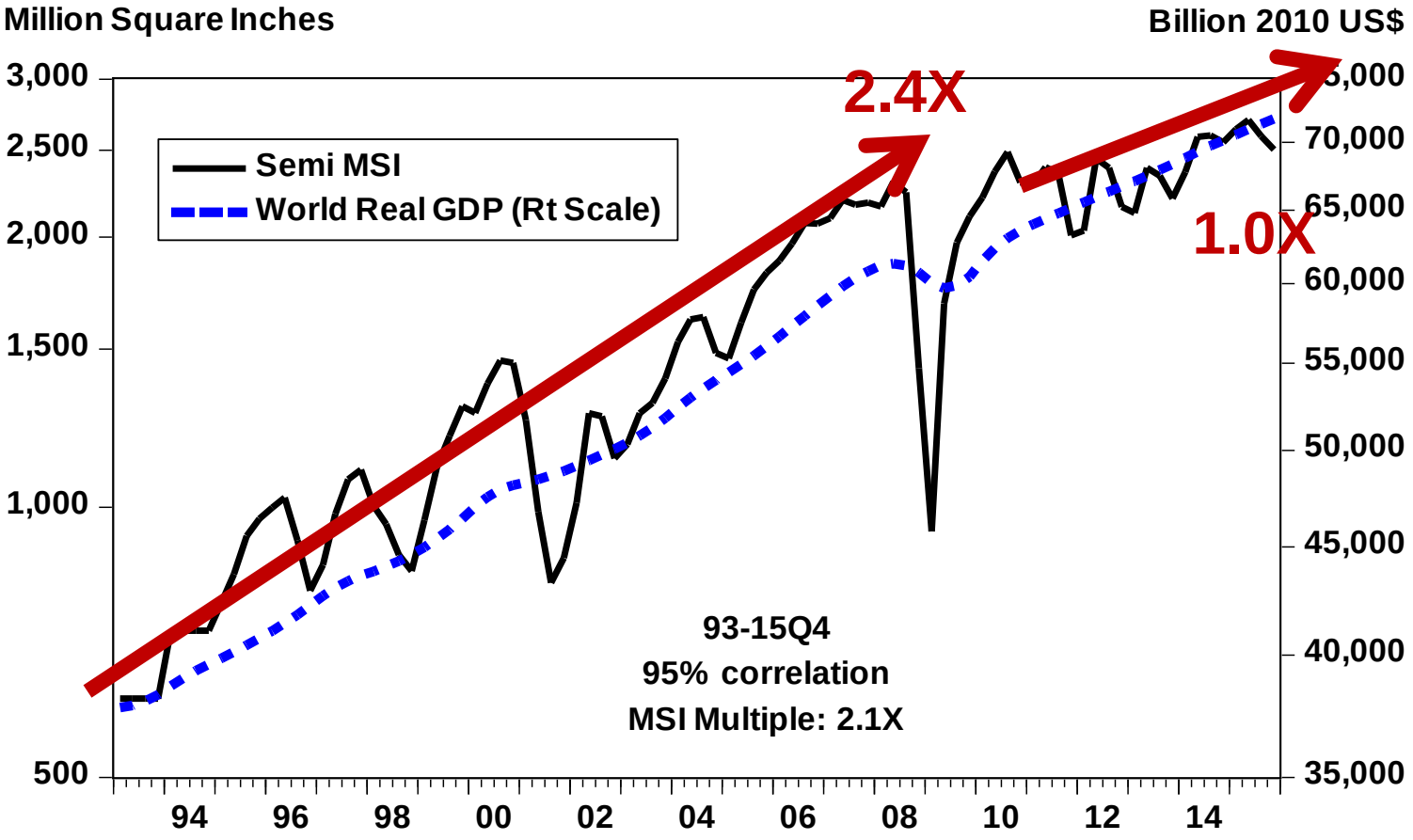
– Semi	– Packaging	– Nano Technology
– LCD	– PV	– LED/ Compound Semi

Customer Base in Semiconductors



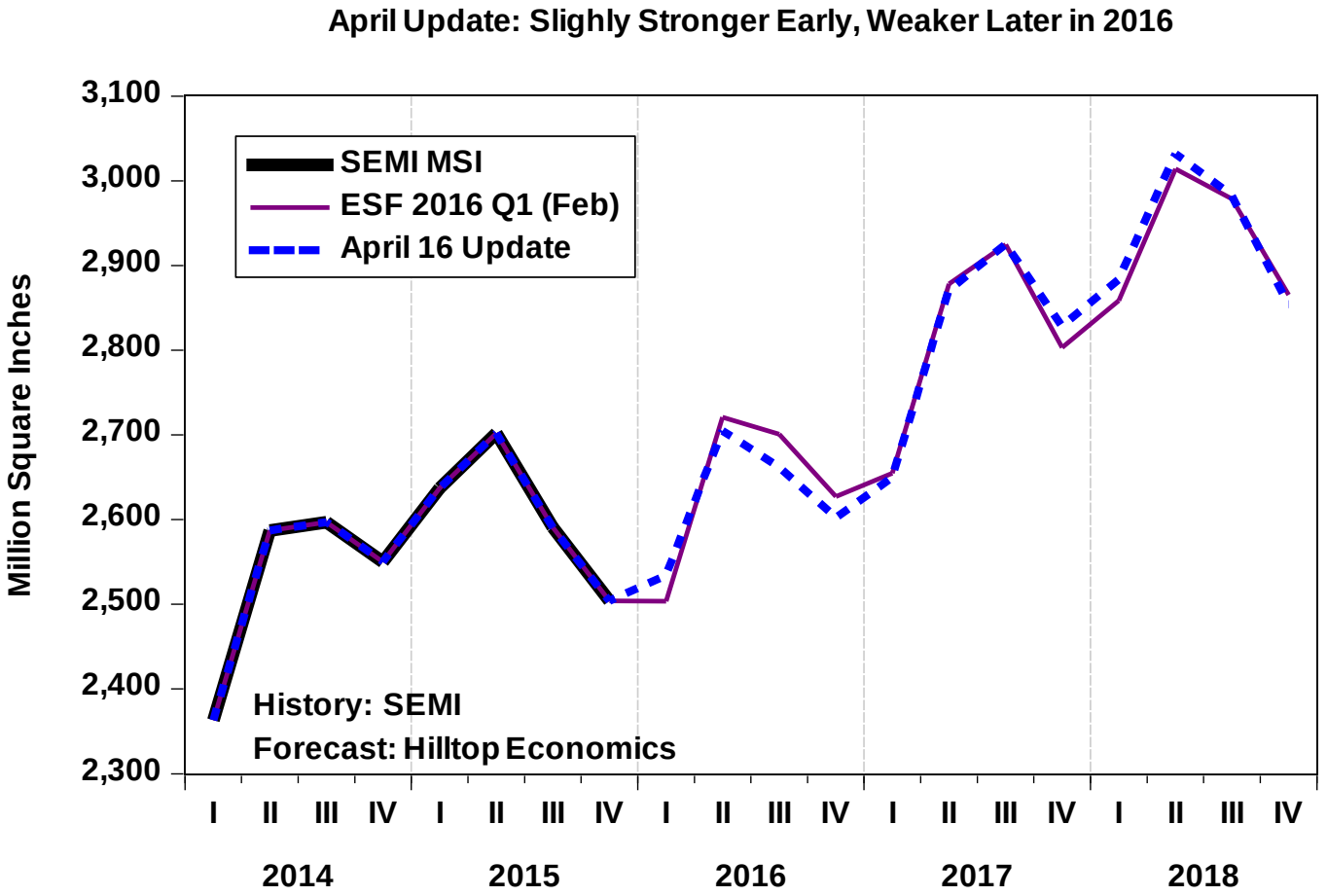
Where Have We Been and Where are We Going?

Silicon Follows GDP Closely

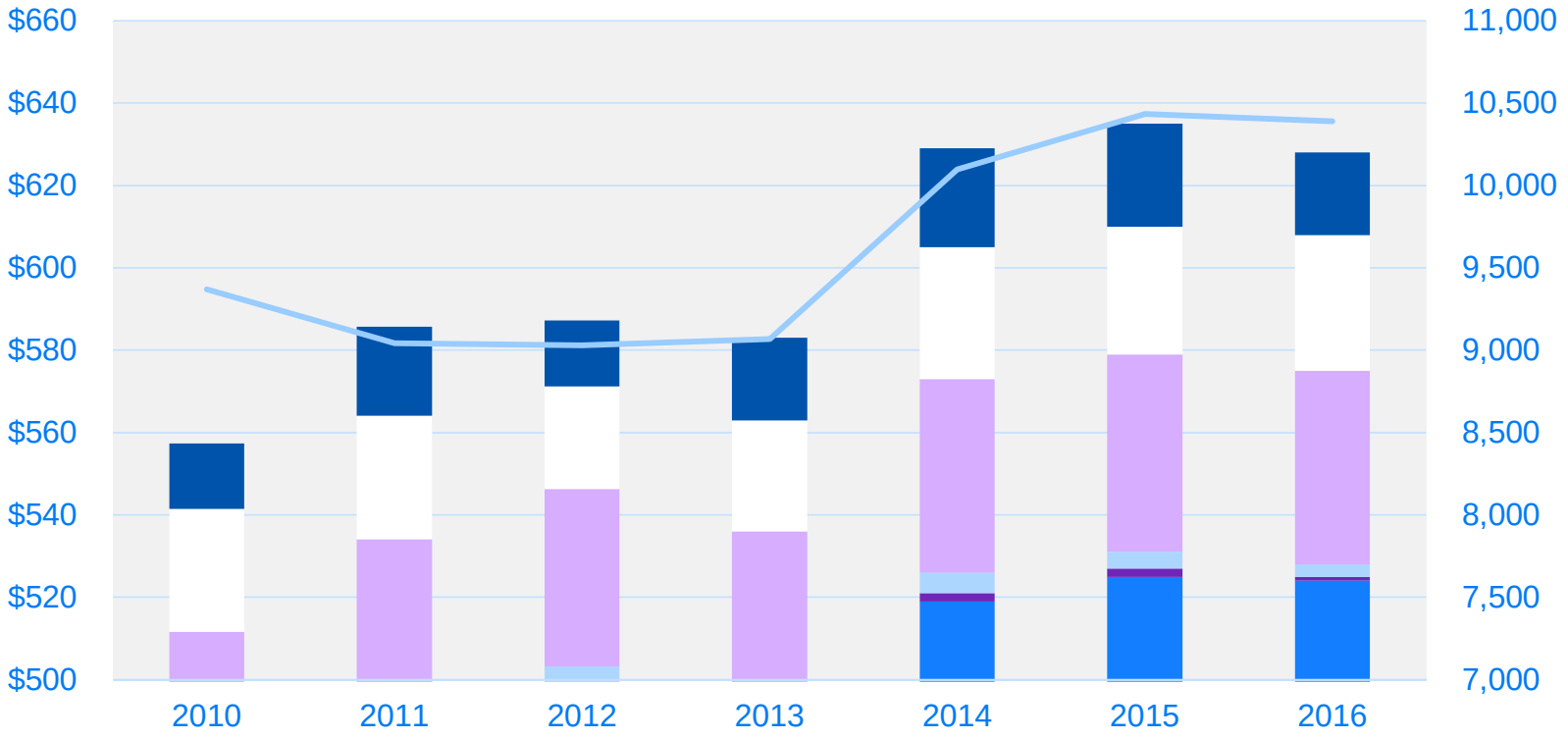


Source: Hilltop Economics

Linx Econometric Semiconductor Forecast



Sputter Target Market $M Vs. MSI



Electronic System Growth Drivers

Internet of Things Much hyped driver of billions of networked devices generating information for governmental, commercial, consumer, medical, and other information systems	**Virtual Reality** Creation of virtual displays of real and simulated environments for military, consumer, commercial and other applications, usually through a novel head display
Artificial Intelligence Computer based intelligent learning systems	**Autonomous Vehicles** Sensor systems supporting vehicle based computer systems offering various degrees of driver assistance including fully autonomous driverless vehicles.

Growth Drivers

Electronic System Growth Drivers

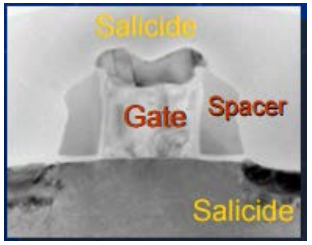
Driver	Need	Impact
IOT	Cloud compute Communications Distributed Devices	Logic Memory Analog Modems
Virtual Reality	Computational Power Graphics	Logic / Graphics Memory Analog
Artificial Intelligence	Computational Power	Logic Memory
Autonomous Vehicles	Computational Power Sensor devices Distributed Devices	Logic / Graphics Analog Power Sensors

Scaling Trends

ITRS 2.0

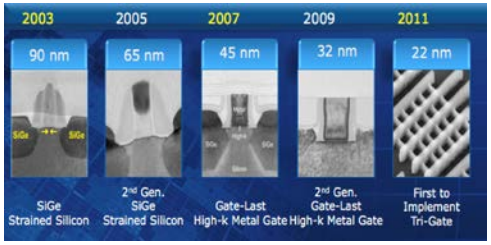
Geometric Scaling, 1975 - 2003

Reduction of horizontal and vertical physical dimensions, combined with improved performance of planar transistors.



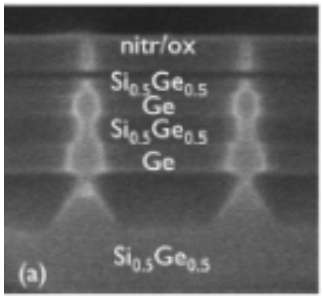
Equivalent Scaling, 2004 - 2020

Reduction of horizontal dimensions only, introduction of new materials, and new physical effects. Vertical structures replace the planar transistor.



3D Power Scaling, 2021 - ?

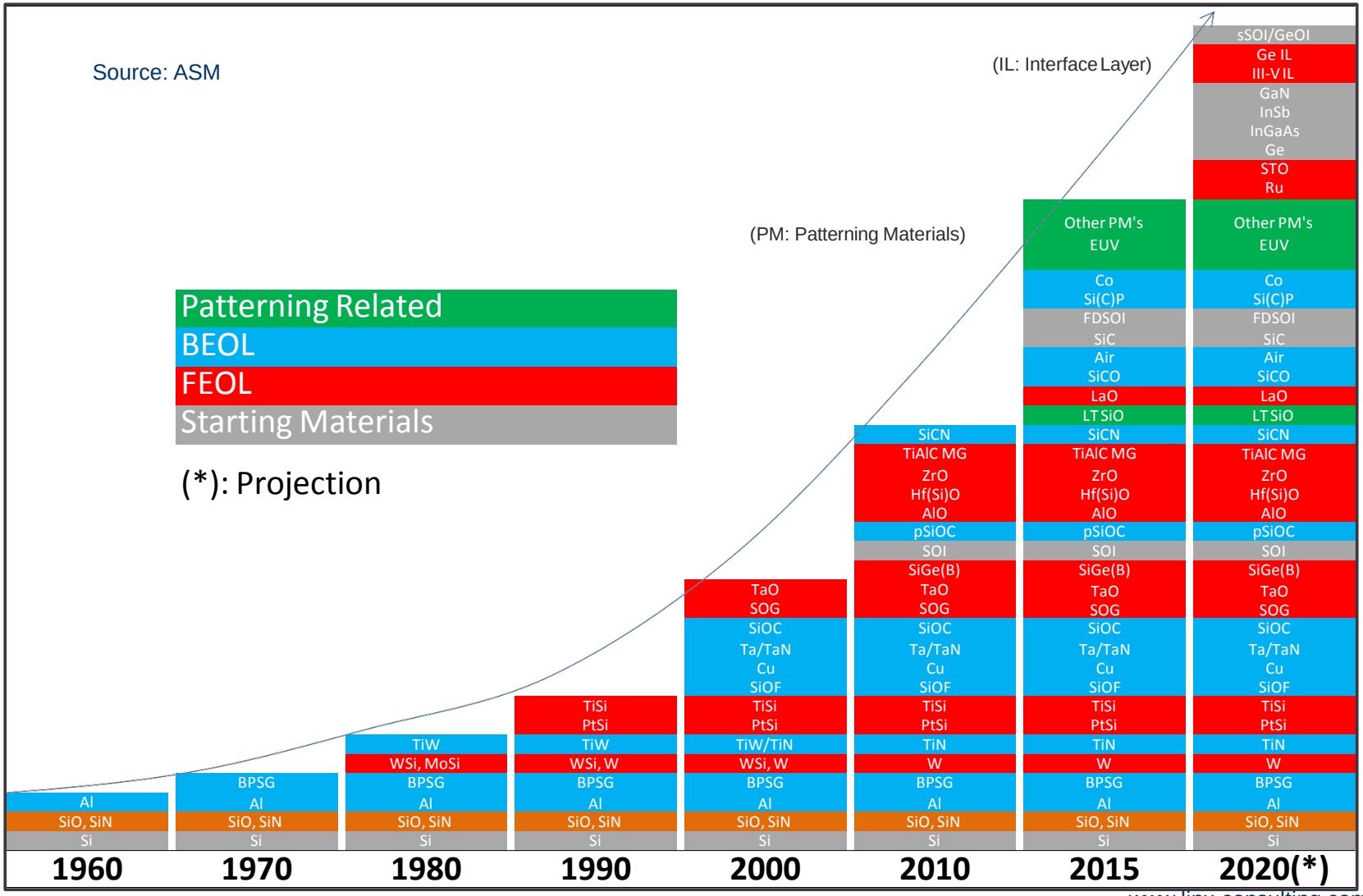
Transition to vertical device structures. Heterogeneous integration with reduced power consumption.



Source: Gargini – ITRS 2.0

Scaling Trends

Materials That Enable Moore's Law



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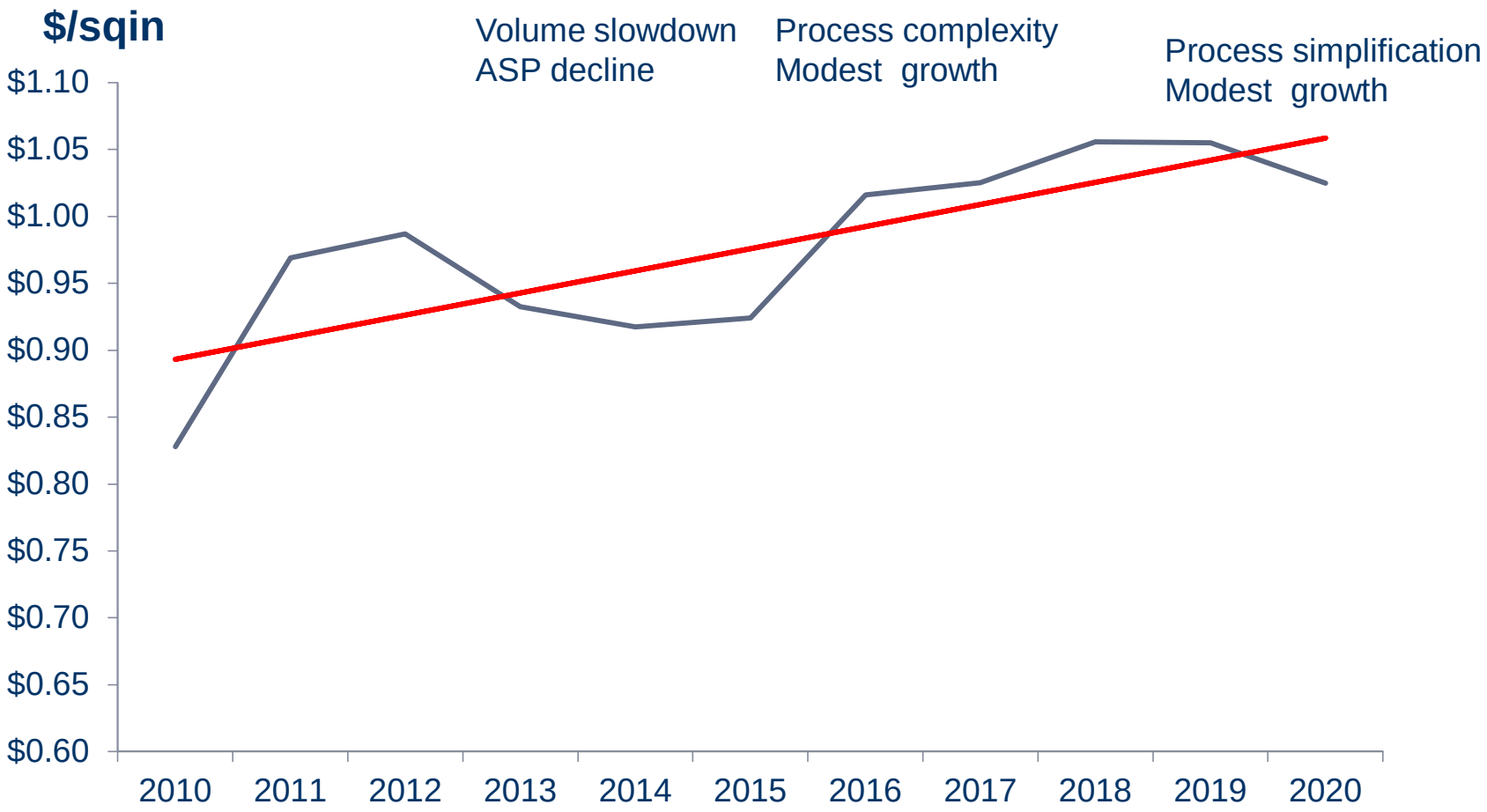
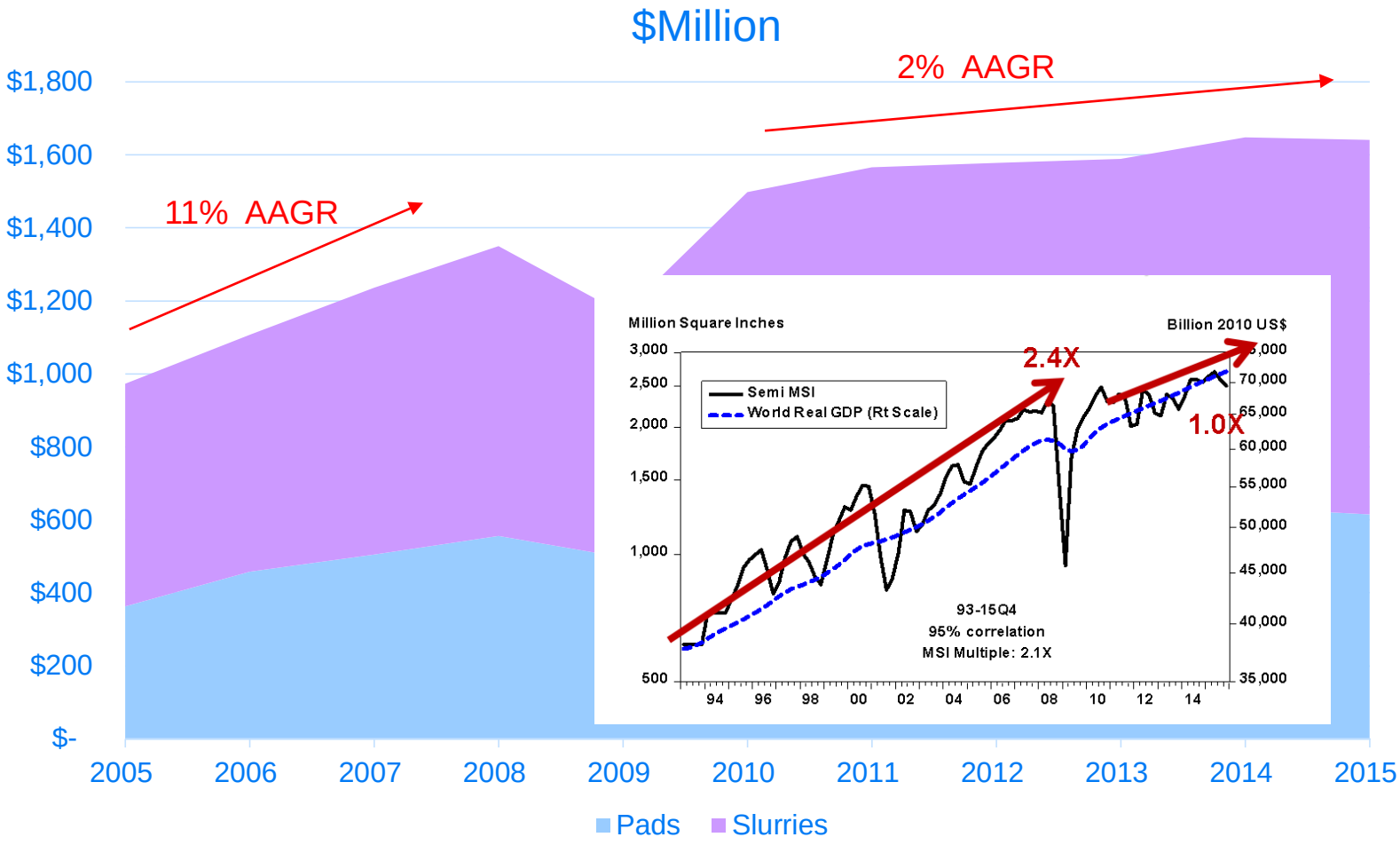
Scaling Trends

Linx Materials Index

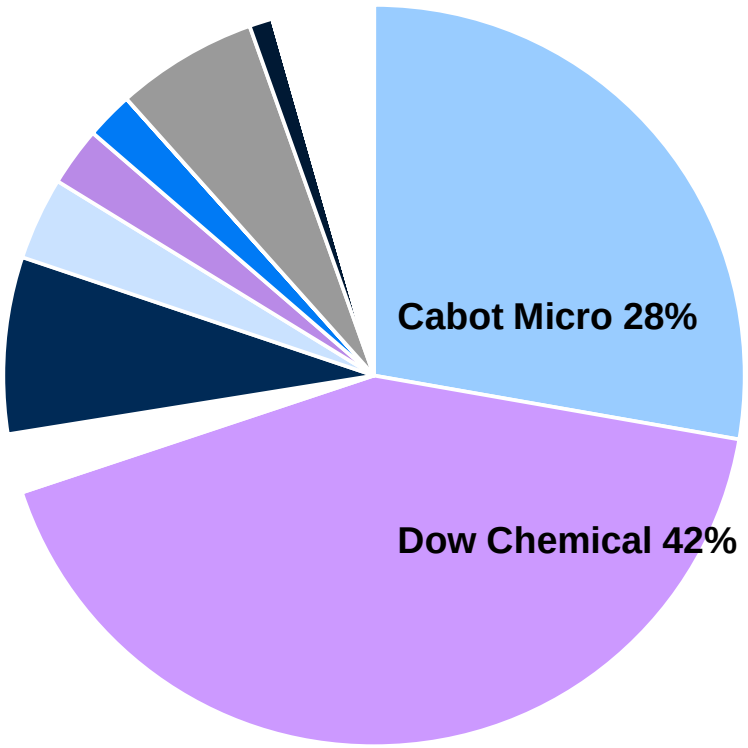


10 Year Look at CMP Consumables

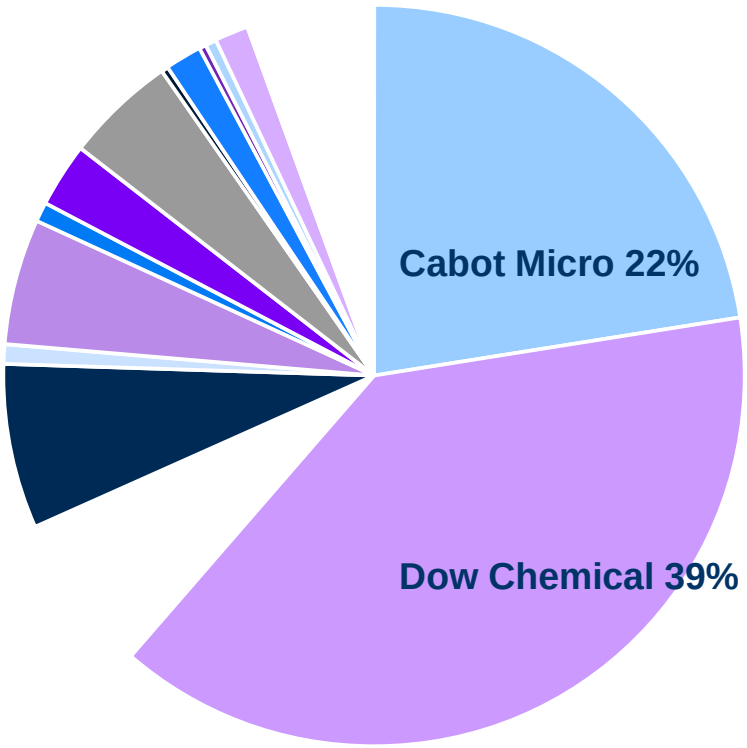


10 Years – Stable Supplier Base
Slurries & Pads

2005 Revenue $M



2015 revenue $M



Industry Evolution

The Challenge

Defectivity Paradigm Shift at 20nm

1. Pursuit of Moore's Law is driving ever increasing design innovation, process sensitivity & complexity
2. Paradigm shift in thoughts about what we did not care about earlier in >20nm era & what we care to control now!
   - Complex Chemistry: Compatibility Issues
   - New Defect Sources, increase Defect Sensitivity
3. Metrology techniques of all types are challenged to provide sufficient sensitivity for early detection & prevention
   - Supplier Infrastructure Development needed for better defect detection & characterization
   - Metrology and Quality Control
4. Proactive engagement and collaboration across the supply chain are essential to HVM readiness

Source: A. Sengupta, Intel. Semicon West 2015

Defectivity

- Real-time metrology is practically impossible.
- In-line metrology is challenged to measure critical particle sizes below 20nm
  - High cost of systems
  - Off-line analysis to augment particle characterization

- Optical (particle detection) systems such as SP3 and SP5 are identifying new defects
  - On-wafer metrology has become the only approach able to show defects.
  - In many cases it is possible to identify the source from on-wafer analysis.
  - The expectation for particle shedding, and contamination continues to reduce.

- Killer defects, or critical particles are now in the order of 10 or 20 nm.
  - On-wafer analysis is struggling to define particles sizes or discriminate defects as residues or discrete solids.
  - Defect sources vary from chemicals, water, seals, filters, piping etc.

- Equipment suppliers are driving to deliver ultraclean products which are certified with the latest analytical techniques, and targeted at delivering best possible performance.

The Challenge

Wafer Fab Expectations

1. **Suppliers should use best practices for control of materials, manufacturing equipment, and components**
   - Close sub supplier collaboration and integrated quality systems; Vertical integration where possible
   - Material and component control is critical
     - Material and process control critical
     - SPC and excursion control is key
     - Sub-supplier involvement in quality is necessary

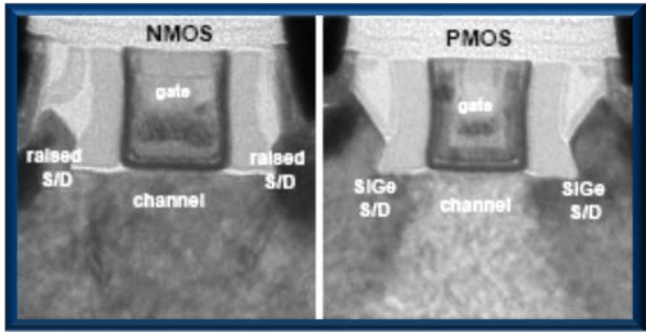
2. **Advanced statistical process control**
   - Feed forward and feedback SPC
   - Sophisticated analytical tools
   - Metrology and analysis gaps, demand collaboration between suppliers and users.

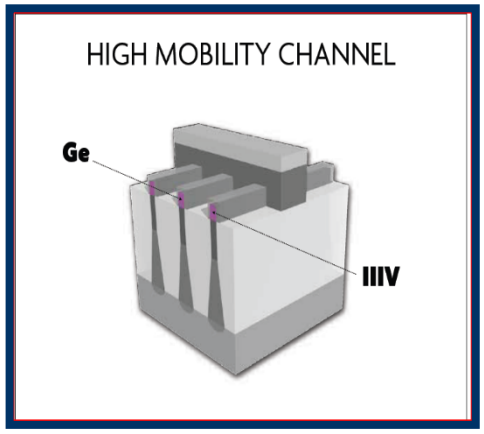
3. **Holistic approach to defect control and Design for cost and environmental impact**
   - Collaborative problem-solving helps identify problems quicker, and implement better solutions
   - Products and systems need to be optimized for advanced node chemistries and processes Aqueous and environmentally friendly formulations are preferred
   - Standardization required to reduce cost

The Challenge

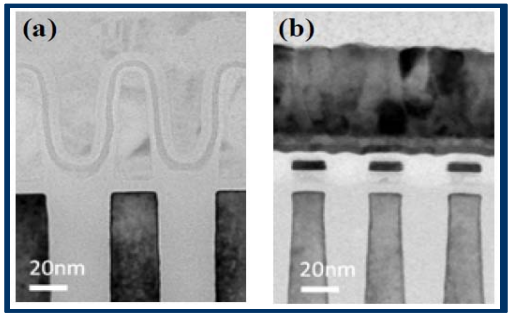
The Move To 3D and HAR Structures

Logic

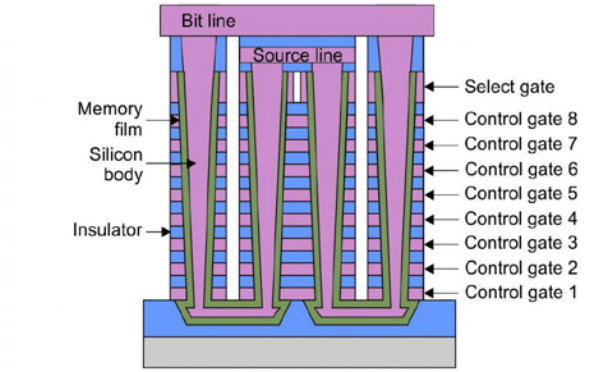




NAND

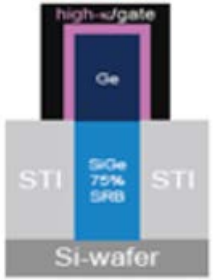


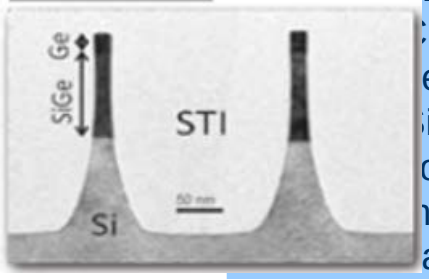
EDN Network



The Challenge

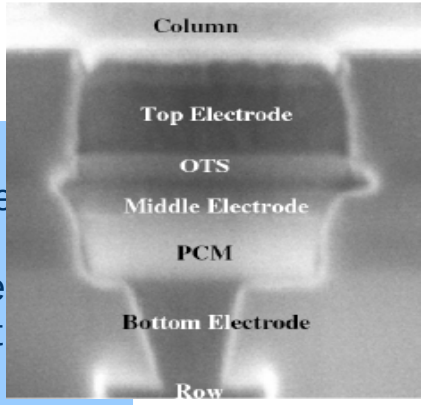
Implications





Logic

- Continued introduction of new materials including SiGe and Ge, with new contacts and MG materials
- Introduction of horizontal nanowire structures



Memory

- 3D Structures are he stay.
- Novel memory syste will enter the market some unique CMP challenges

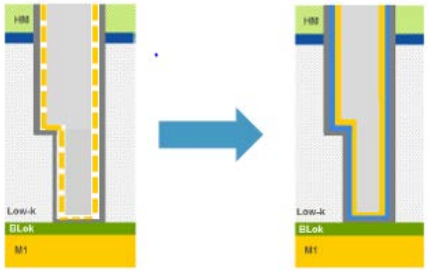
BEOL Logic

- Introduction of new bulk conductors, barriers and liners to minimize RC

200mm Capacity

- Older node capacity expected to stay tight.
- Look for productivity based CMP solutions implemented to postpone capex

CVD Co improves Cu wetting



Paths Forward for Consumables

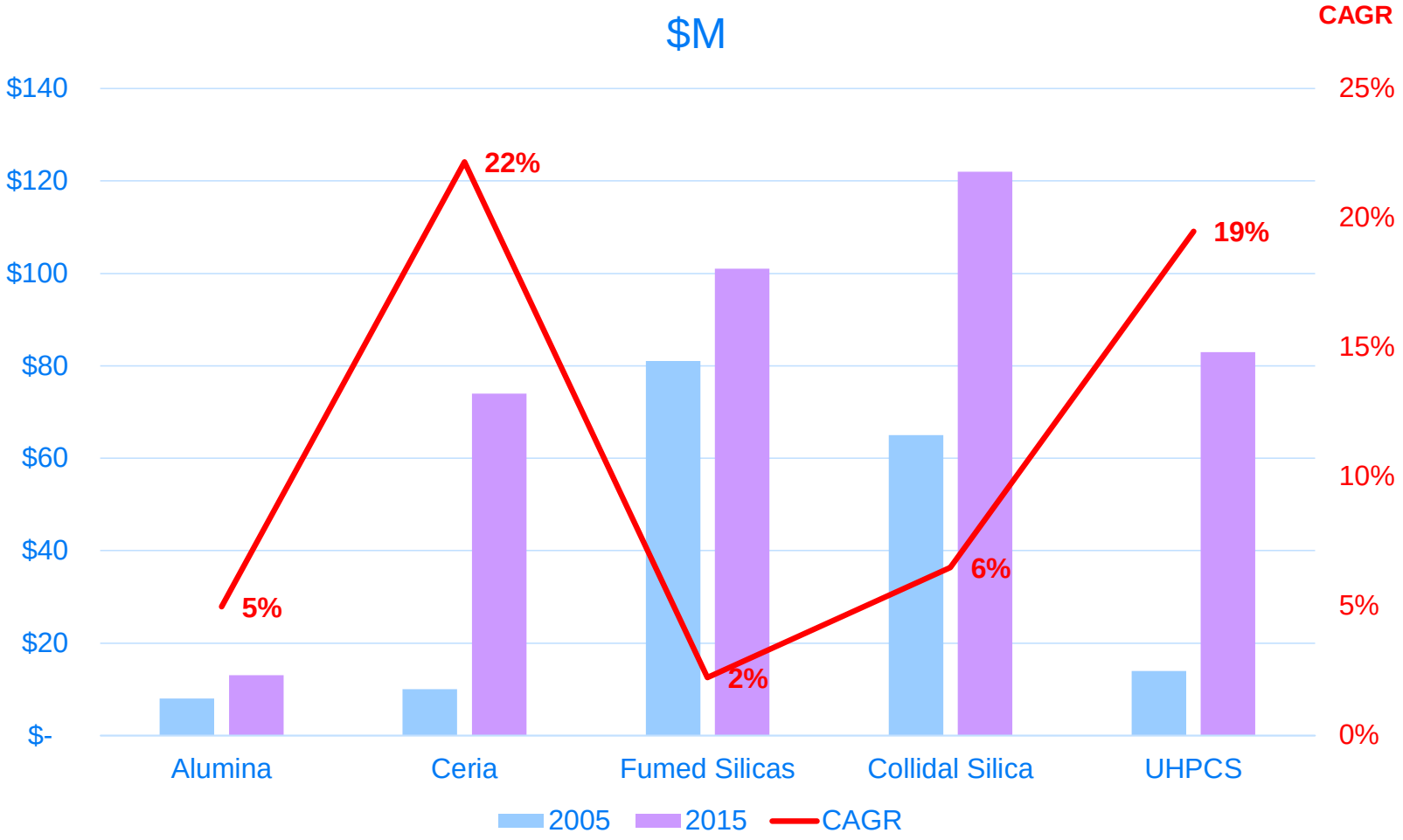
ADVANCED / SPECIALTY

- Enable novel FEOL polishes and architectures:
  - Horizontal Nano wire
  - High mobility Channel, contacts and MG
- Enable new memory technologies
  - PCM
  - STT MRAM
- Enable new BEOL materials
  - Cobalt, Ru
  - Alternative/self forming barrier
- Heterogeneous integration
- Solve productivity and defectivity problems

COMMODITY

- Have evolved from current materials base
- Need to be drop-in ready
- Are readily copied
- Will compete based on cost

Evolution of CMP Abrasives



Consolidation Leading to Larger Suppliers

China

- Continued acquisition and activity from multiple companies.
- Leveraged government equity positions to enable significant size acquisitions.

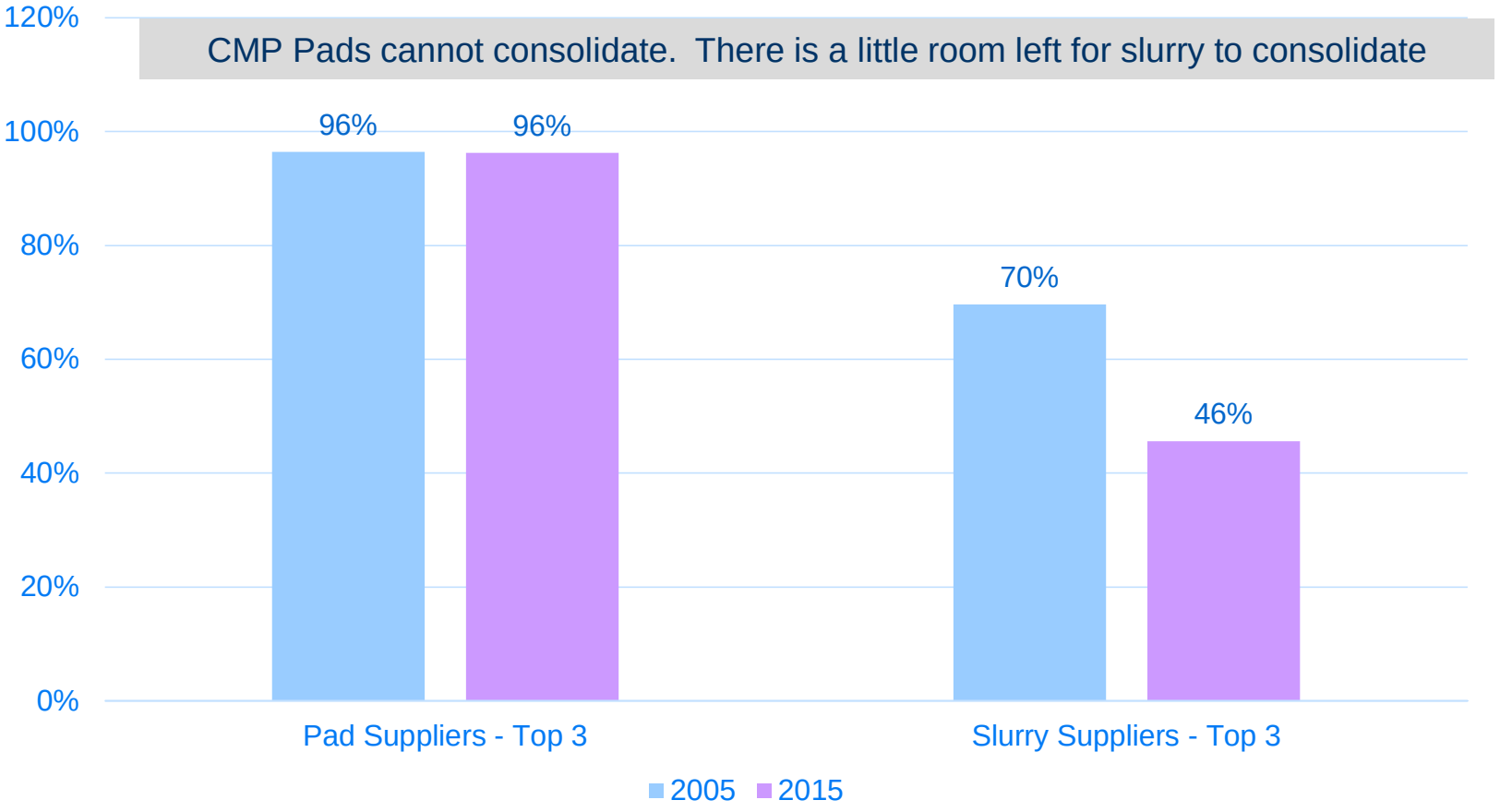
Specialties Model is still Valued!

Acquisition Landscape

- Tsinghua Unigroup (China): Spreadtrum, RDA, WD, Powetech…..
- Lam Research – KLA/Tencor
- Beijing E-Town Investment (China) – Mattson Technology Materials
- KMG - OMG + General Chemical
- Entegris - ATMI
- Merck - AZ
- Merck – Sigma Aldrich & Solmet
- Cabot Microelectronics - NexPlanar
- Wonik – Nova-Kem
- NATA (China) - Kempur
- Air Liquide – Air Gas
- Air Products – Versum Spinout
- SK - OCIM
- Dow Chemical – Dow Corning
- Dow Chemical - Dupont

Will CMP Consolidate ?

Supplier Share Evolution Over the Last 10 Years



Pads include Cabot Micro acquisition of NexPlanar

Conclusions

- Drivers for industry growth are changing, but there will continued demand for current device types
- Roadmap trends will drive to 3D device architectures in the medium to long term. System specific hybrid packages, device types, and device architectures will extend the roadmap.
- New device architectures will shift requirements of critical materials for different devices.
  - Lithography extension is a primary cost driver.
  - 3D devices will challenge aspect ratios, placing focus on etch and deposition capabilities.
- The shift from planar scaling to 3D will extend into the packaging realm as some functionality and interconnect is moved into the wafer level package.
- Quality and defectivity requirements continue to be incredibly challenging, and require supply chain engagement.