Semiconductor Metrology: Past Present and Future

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g dan hutcheson
Metrology Time Machine: Dawn of the IC

• Microscopes dominate
  • Wafers handheld under lights for film thickness uniformity
• SEMs used for off-line FA
• Demand first driven by military/aerospace
  • A computer w/tubes would be Empire State building sized for a moon shot

Wafer Inspection in the 60’s at Fairchild Semiconductor
The Leading Edge: ~1980
Metrology Time Machine: 1980’s

Two Philosophical Approaches:

- Inspect to Cull
- Make it Perfect
Breaking the 1μ Barrier

Move from 100 to 125 to 150mm

SPC, CD, and Overlay Control enter the scene

Optical dead Electrons & X-rays on the way

Move from Automated Microscopes to Inspection

Ramp yields go from 20% to 60%
History of Inspection

Defect focus is on coarse particles (1-100 Microns)

Automated Material Handling

1980’s → 1990’s → 2000’s → 2010’s → Beyond
Yield shifts gear in the 80’s

- **It started in memory**
  - And would follow in logic
  - By the 90’s
- **Metrology** and steppers
  - made it possible
- **Japan**’s great chip makers of the day brought a **live or die incentive** to the battlefield.
Metrology Time Machine: 1980’s

KLA 2020, Circa 1984

The tool that sparked the yield management revolution
Metrology Time Machine: 1980’s
The Leading Edge: ~1985
Yield dividend would drive metrology

- Ramp yields went from 20% to 60%
  - Between 1980 and 2000
- Yield added an additional kick to Moore’s Law
  - Only possible with process diagnostic tools
A New Paradigm Emerges:

Metrology Time Machine: 1990’s

Inspect to Cull

Make it Perfect

Inspect to Manage
The Leading Edge: ~1990
The Leading Edge Issues: 1990’s

- Getting to “deep-sub-micron”
- Move from 150mm to 200mm
- SPC rises to the top of the control issues
- Optical dead for metrology… Electrons on the way
- Threat of Japan
- Rise of the Tigers: Korea & Taiwan
@ ISS Europe 1992:

There was a …

- Can’t beat Japan attitude
  - They “won by cheating”
- But Europe was holding its own ground
  - Doing a much better job than America

Why such a Dark Outlook?

Source: ISS 1992, Hartwig Reull
What some said @ ISS Europe 1992:

- Fabs getting too expensive
- That Europe lacked:
  - Strategic Planning
  - Critical Scale
  - Lacked a modern economic policy
    - Adam Smith vs. Keiretsu

Source: ISS 1992, Hartwig Reull
History of Inspection

1980’s: Defect focus is on coarse particles (1-100 Microns) with Automated Material Handling.

1990’s: Emergence of Yield Management with Defect focus on tools.

2000’s: Machines replace Humans.

2010’s: Beyond.
Metrology Time Machine: 1990’s
Hitachi S6000

Features

1. Outstanding high resolution of 8 nm at 1 kV operation.
   The S-6100 allows a high resolution image of 8 nm or better at a low operating voltage of 1 kV and at a back-lit TV monitor rate on a CRT monitor. This high performance allows CD measurement at deep submicron patterns of VLSI which is moving from the present 4M bits to 96M bits or even 64M bits. Demonstrated at the right photo typical images of deep submicron processed patterns.

2. Software compatibility with the S-6000.
   The S-6100 has the same operating controls and measurement software as the S-6000. Operators who have been trained on the S-6000 can operate the S-6100 without any problem. Built-in instruments use the same operating commands so that there will be no confusion among multiple operators.

3. Optional accessory compatibility with the S-6000.
   Most optional accessories for the S-6000 are available for the S-6100 also. These options include data transfer, remote control via external computer, raster function, edge roughness measurement, photo CRT unit, recording camera, etc.

Specifications

1. **PERFORMANCE**
   - **WATER SIZE:** 4.5" x 6" diameter (130 x 150 mm)
   - **Electron Gun:** Single filament, linear position controlled
   - **Accelerating Voltage:** 1 kV
   - **镊子 Type:** Cross type (both horizontal and vertical directions)
   - **Measurement range:** 0.1 - 100 nm
   - **Repeatability:** ± 3% of 100 nm (one hundred nm)

2. **SAMPLE STAGE**
   - ** Movement:** X: 150 mm, Y: 150 mm
   - **Drive:** CPU control (both X and Y)

3. **SAMPLE LOADING**
   - **WATER Holder:** One 4", 5", or 6" holder (additional holders of option)
   - **Proof of Circuit:** Automatic (diameter < 0.01 mm) or optional (standard)
   - **Water transfer:** Automatic (diameter < 0.01 mm) or optional (standard)

4. **ELECTRON OPTICS**
   - **Electron Gun:** Cold field emission source
   - **Accelerating Voltage:** 0.1 - 13 kV (13 kV fixed)

5. **DISPLAY SYSTEM**
   - **Screen:** 12" flat panel, 190 x 190 mm x 1 (optional)
   - **Screen Mode:** Averaging mode

6. **VACUUM SYSTEM**
   - **Vacuum Pump:** Dual type, turbo molecular pump 0.5 m³/s for atomic layer deposition

7. **SECURITY**
   - **Remote Control:** Emergency power-off switches provided

Optional Accessories

- Photo CRT
- 4" x 6" camera (optional)
- Printer (optional unit)
- Water holder (x 2 units)
- Cross section holder
- Arc compressor
- Electron gun
- Edge roughness measurement

For further information, please contact your nearest sales representative.
Metrology Time Machine: 1990’s

Even KLA got on the e-beam bandwagon

• Optical would die out after 200nm …

• But we still were not in the nanochip era
  • They were microchips
Metrology Time Machine: 1990’s

The big change was the KLA’s concept of…

**Yield Management**

Developed in Korea with Samsung, it would upend the memory market

**Samsung** was trying to get the most **good die-out-per-wafer**
by inspecting to cull out the yield killers

**Japan** was stuck on the old **make-it-perfect**
philosophy: they were after **the perfect cleanroom**
Metrology Time Machine: 1990’s

We were starting to **put it all together** with **data visualization** tools linked to distributed inspection and metrology platforms.

It may not have worked well, but it was **visionary** – this was **the future**.
Metrology Time Machine: 1990’s

**Lithography** was rising to the top of the issues

**Overlay Control** broke into the fab and became an in-line process step
Metrology Time Machine: 1990’s

**In the 90’s**

- Process diagnostic tools used across …
  - 12 production areas
  - 11+ critical applications
- Versus 1 and 2 before 1980
The Leading Edge: ~1995
Metrology Time Machine: As the 1990’s close, you still see it as **humans clustered around a tool** … but it’s data not images that are being looked at
Yield dividend continues to drive metrology

- But it’s no longer the good-die, bad-die, and ugly story
- Profits now come from sort yields
  - Better performance yields better prices
- It’s now a good, better, best focus
Cleanroom Particles were no longer the problem. *Tools were the problem*
The Leading Edge Issues: 2000’s

- Microchips become Nanochips
  - The first mass-produced nantecnology

- Move from 200mm to 300mm

- CDU, LER, and Overlay Control become big contributors to profitability

- Electrons learn to live with their bigger brother: Optics

- Millennium mania, the dot-com bust, and the Great Recession = the lost decade

- Ramp yields go from 60% to 80% for memory
History of Inspection

- **Defect focus is on coarse particles (1-100 Microns)**
- **Emergence of Yield Management**
- **Yield Excursions drop to hours**
- **Fab costs rise from $1B to $5B by EoD**
- **3D enters the fab with AFMs**

**1980’s**
- Automated Material Handling
- Defect focus is on coarse particles

**1990’s**
- Emergence of Yield Management
- Machines replace Humans

**2000’s**
- Yield Excursions drop to hours
- Fab costs rise from $1B to $5B by EoD
- 3D enters the fab with AFMs

**Beyond**
Irwin Jacobs is trying to merge these two

is a book store

is a start-up and like 1000’s of other internet startups ... it has no Business Model
The 2000’s: the Lost Decade

- Focus shifted to M&A
- Rationalization to control cost
Microchips become Nanochips
The first mass-produced nanotechnology

We flirt with 450mm

New materials and devices

CDU, LER, Overlay Control are the biggest contributors to profitability

3D emerges everywhere

Yields are expected
Fast ramps and time-to-market
The Leading Edge: ~2010
**History of Inspection**

- **1980’s:** Defect focus is on coarse particles (1-100 Microns)
- **1990’s:** Emergence of Yield Management
  - Defect focus on tools
  - Automated Material Handling
  - Machines replace Humans
- **2000’s:** Yield Excursions drop to hours
  - Fab costs rise from $1B to $5B by EoD
  - 3D enters the fab with AFMs
- **2010’s:** HKMG & finFET
  - Deep Learning 1st applied
  - Fab costs >$15B by EoD
  - 3D goes in-line
- **Beyond:**

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The Leading Edge: Today

VLSI research ... intelligence to make better decisions faster
Metrology Technologies are Complementary

Proof: Share of optical relative to e-beam is slightly higher than it was 35 years ago

Both core technologies have not lost their usefulness. They have enhanced it with many new applications.
Why Complementary Metrology Technologies are Triaged in the Fab

<table>
<thead>
<tr>
<th>E-beam</th>
<th>Brightfield</th>
<th>Darkfield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Affordability</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>Resolving Power</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>Coverage</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Throughput</td>
<td>High</td>
</tr>
</tbody>
</table>
Every nanometer matters in 3D patterning

You can’t fix what you can’t find
You can’t control what you can’t measure

**Smaller Process Window**

**Metrology / Performance**

Source: KLA-Tencor

**Metrology** provides comprehensive data to decipher pattern issues

FinFET key parametric measurements
Non-Litho Errors Dominate Patterning

Emergence of Non-Litho Errors leads to more complex patterning control

Process control inside and outside the litho cell is critical for meeting patterning requirements

LELE CDU/Overlay budget example
Source: KLA-Tencor

CDU = Critical Dimension Uniformity
PPE = Pattern Placement Error
Dimensions of Process Control

• x, y & z

• **Feed-forward** in addition to Feedback
  – Optimized algorithms
  – Ability to correct process backward and forward

Source: KLA-Tencor’s 5D™ Patterning Control
SpectraFilm Capabilities  
supports a diverse range of film applications

- **BBSE**
  - Broadband Spectroscopic Ellipsometer

- **SWE**
  - Single Wavelength Ellipsometer

- **IRSE**
  - Infrared Spectroscopic Ellipsometer

**Targeted Applications**

<table>
<thead>
<tr>
<th>Thin Multi-Layer Films</th>
<th>Thick Single Layer Films</th>
<th>Thick Multi-Layer Films</th>
<th>Extreme Multi-Layer Films</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO, ONO, SiGe</td>
<td>Oxide, Photo Resist, α-Carbon</td>
<td>DARC/Oxide, OPO, ULK Stack</td>
<td>3D NAND</td>
</tr>
</tbody>
</table>

Source: KLA-Tencor
Fab-Wide Process Control

Metrology data drives feedback and feed forward control loops

Address fab-wide sources of pattern variation
• Optimize processes that can affect patterning
• Augment information available for scanner corrections

Source: KLA-Tencor
Metrology Time Machine: 2020 & Beyond

Tackling the 3rd Dimension

Information Turns

Jump from Deep Learning to Cognitive AI

Process diagnostics will be much more about how the machines learn.
History of Inspection

**Value**

- **Defect focus is on coarse particles**
  1-100 Microns

- **Automated Material Handling**

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- **Emergence of Yield Management**

  **Defect focus on tools**

- **Machines replace Humans**

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- **Yield Excursions drop to hours**

  **Fab costs rise from $1B to $5B by EoD**

- **3D enters the fab with AFMs**

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- **Yield Excursions drop to minutes**

  **Fab costs >$15B by EoD**

- **3D goes in-line**

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- **HKMG & finFET Deep Learning 1st applied**

- **More Innovation Needed**

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**Beyond**
Growth has come back

While it won’t be the go-go era before 2000, it will still be solid growth

As long as we continue to deliver on new technology
The Leading Edge: Tomorrow

Amazon
Microsoft
Google
Facebook
Tesla
IBM

And???
Metrology Time Machine: What’s After Tomorrow?

Cognitive Computing
• The wave after IoT/Cloud
• Watson is 5 years old
  – Won Jeopardy in 2001
  – Now it’s working with Doctors to solve cancer
  – It is a decision making tool
    • Not a replacement for decision makers

Watson knows what …
you don't know,
what you forgot,
or forgot that you forgot.
Cognitive and Process Diagnostics

- **AI as the Next Big Thing. It’s that and more**
  - The reason is similar to our history of NBTs
- **Cognitive is going to require completely new types of device structures and architectures.**
  - More compute performance that uses less power
  - That is the inalienable truth of the history of silicon.
  - That means better ways to move that data between memory and processor
- **Cognitive will be as disruptive as what’s come before,**
  - Smart is not good enough, Smart is the new dumb
    - Things have to think ahead
    - They have to anticipate
    - They have to decide and act
    - *And that’s the future of silicon*
- **The question is …**
  - **What to do in the cognitive fab?**
    - *Metrology on steroids with FF & FB*
    - *How to apply the new technology?*
    - *IoT + Big Data + Cloud + …*
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