2005 International Conference on Characterization and Metrology for ULSI Technology, Dallas, USA
The Role of a Physical Analysis Laboratory in a 300 mm IC Development & Manufacturing Centre

Outline

• Business challenges

• Crolles 2 Alliance

• Characterization and Metrology strategy
  – Microscopy, Materials Analysis
  – Full wafer systems, benefits & economics
  – Failure Analysis, the need for better precision & resolution

• Conclusions & Perspectives
IC Manufacturing Trends

Complexity increase…

Price erosion…

Assuming all digital products: Product costs reduced by ~ 50% per technology

Fab Costs explosion…

Design Costs explosion…

Source: Dataquest

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Semiconductor Business Challenges

The Dollar Gap…

The Winner takes it all…

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Crolles 2 Alliance Strategy

*to capture market our priorities are:*

- **First time right**
- **Time to Market (TTM)**
  - Technology development, prototyping
- **Time to Volume (TTV)**
  - Process control & Yield ramp

*Cycle time and Yield are key!*
Crolles 2: The Joint R&D and Pilot Fab

- Partnership between ST Philips and Freescale
  - R&D & pilot fab Crolles 2
  - 120, 90, 65, 45nm processes
  - Bulk CMOS, SOI, EDRAM
  - Std Libraries shared
  - First products in 2003

- 300 mm Pilot line
  - Clean room: 5000 m²
  - 1.4 B$ investment
  - 1200 people
Crolles 2: CMOS Technology Roadmap

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>Node</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>CMOS</td>
<td>90 nm</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>CMOS</td>
<td>65 nm</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Advanced R&amp;D</td>
<td>45 nm</td>
<td>Production</td>
</tr>
<tr>
<td>2004</td>
<td>Advanced R&amp;D</td>
<td>32 nm</td>
<td></td>
</tr>
</tbody>
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- **1° silicon**: Green circles
- **Technology models**: Green triangles
- **Pilot Projects**: Green plus signs

March 2005
Crolles 2: Yield and Learning cycles
Off-line Characterization support

Without fault isolation
- R&D support
- Process development

With fault isolation
- Yield loss analysis

Physical characterization
- Voltage Contrast
  - Test structure
- OBIRCH
  - Test structure
  - Product
- Bitmap Memories

- FIB, SEM, TEM, EELS, AES, TOF-SIMS, XRR, XRD...
Off-line Characterization support

**Without fault isolation**
- R&D support
- Process development

**With fault isolation**
- Yield loss analysis

**Voltage Contrast**
- Test structure

**OBIRCH**
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- Product

**Bitmap Memories**

**Physical characterization**
- FIB, SEM, TEM, EELS, AES, TOF-SIMS, XRR, XRD…
MICROSCOPY
Physical Characterization: Microscopy

Transistor scaling...

180 nm transistor

90 nm transistor

65 nm transistor

32 nm transistor
Structural analysis: SEM / TEM

Details difficult to detect with SEM

- 180 nm Technology: 90% SEM – 10% TEM
- 65 nm Technology: 55% SEM – 45% TEM
Microscopy: SEM is out…!

65 and 45 nm CMOS developments require TEM…
Microscopy: TEM is in… but we need more!

SEM volume stagnates, TEM volume increases…

But TEM is not a volume technique yet…
Microscopy: Economics of SEM vs. TEM

• SEM activity until now
  – Volume: 3000 – 5000 samples / year
  – Cycle time: 1 – 5 days
  – Equipment: 3 SEM’s, 2 FIB’s, ~ 4 M$ Capex
  \[ \Rightarrow \sim 200 – 300 \$ / sample \]

• TEM activity until now
  – Volume: 400 – 800 samples / year
  – Cycle time: 2 – 10 days
  – Equipment: 2 FIB/SEM’s, 2 TEM’s, ~ 7 M$ Capex
  \[ \Rightarrow \sim 2000 – 4000 \$ / sample \]

\[ \Rightarrow Costs / sample is rather prohibitive…. \]
Microscopy: an Industrial TEM line

• Boost TEM volume, improve cycle times
  – Volume: 1500 – 3000 samples / year
  – Cycle time: 1 – 5 days
  – Equipment: 3 FIB/SEM’s, 2 TEM’s, ~ 9 M$ Capex
  – ~ 600 – 1200 $ / sample
    ➔ Focus on high value added TEM data!

• Strategy:
  – 300 mm FIB/SEM for non-destructive sample pluck
  – 300 mm Wafer Return into process flow
  – Small chamber FIB/SEM for final sample preparation
  – Fully equipped (EELS/EDX) TEM systems for analysis
TEM lamella creation process

90 % yield

Chunk milling process and In-situ extraction in 300 mm FIB/SEM system

80 % yield

Final lamella thinning in small chamber FIB/SEM system
TEM Microscopy: Practical Issues to resolve

Imperfections in the process

Material re-deposition

Insufficient sample height

Needs further optimization of chunking process recipe
TEM Microscopy: Practical Issues to resolve

Bending of thin lamella

Difficulties with TEM alignment!

- FIB milling process induced (Ga implant, heating, …)
- Needs adapted procedures (lamella shape/process)
TEM Microscopy: Practical Issues to resolve

Amorphisation of very thin (< 40 nm) lamella

• FIB induced @ 15 KeV ~ 15 - 20 nm each side
• Low energy (< 2KeV) FIB milling process needed

Amorphous Silicon!
TEM Microscopy: High Value Added data

45 nm Transistor engineering

Process control at atomic level!

2-D spacer shape affects transistor characteristics!
TEM Microscopy: High Value Added data

45 nm SRAM Cell construction analysis

Dimensional control, process anomalies, alignment accuracy etc…
Elevated Source/Drain on SOI substrates

Excessive Silicon etching during surface cleaning steps may influence channel characteristics
TEM Microscopy: High Value Added data

Chemical Analysis via EFTEM, EELS

FEOL
Defective CoSi2

BEOL
Nitride residues

EF-TEM
EELS line scan
Microscopy: Conclusions

• Development of latest technology requires a high quality, fast and volume TEM service.

• Efficient TEM sample preparation is key to success!

• Non-destructive Full wafer sample extraction offers significant advantages for fast learning cycles.

• The overall process still needs to be improved and become more automated in order to arrive at correct TEM volumes.
MATERIALS ANALYSIS
Materials Analysis

• The Materials Analysis group activities:
  – Chemical Analysis (SIMS, µ-AES, ToF-SIMS, XRF)
  – Structural Analysis (XRD, EBSD)
  – Mechanical Analysis (TEM-CBED, µ-Raman spectr.)
  – Metrology Applications development (XRR/XRF, IRSE, µ-XRD, …)

• Full Wafer analysis strategy
  – Easy to operate, Fab compatible, high throughput
  – Non-destructive, several complementary techniques can be used to characterize one wafer/die
  – Easy navigation facilitates Failure Analysis
Materials Analysis: 300 mm Wafer Tools

Full wafer SIMS: allows full wafer process mapping

ALD TiN process A
Chlorine variation = +/-19.6%
25 points analysis, 3.5h

ALD TiN process B
Chlorine variation = +/-9.1%
17 points analysis, 2.5h

Fast and relevant feedback allows rapid Process development cycles
Materials Analysis: 300 mm Wafer Tools

Full wafer μ-XRD : TaN/Ta/Cu seed wafer

XRD at two locations

- XRD Diffraction patterns of thin and thick regions on Ta/Cu wafer.
- Thick Ta with (110) texture seems to induce a strong (111) Cu texture.
Materials Analysis: 300 mm Wafer Tools

Full wafer XPS: Nitrided Gate Oxide monitoring

XPS Nitrogen dose Map (E15 at/cm²)

- XPS does provide both thickness and dose information
- It is possible to predict EOT/CET from in line XPS measurements

Nitrogen dose vs. Thickness

\[
y = 0.1077x + 0.3601 \\
R^2 = 0.9146
\]

\[
y = 0.071475x + 0.584366 \\
R^2 = 0.910584
\]

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Full Wafer SIMS: USJ analysis, Boron

Reduction of SIMS etching energy from 500eV down to 200eV:

depth resolution improves from 1.5nm/decade down to 0.9nm/decade
ToF-SIMS: Clean Room AMC Monitoring

At Room Temperature ~ 30 – 70% of the volatile species desorb from the wafer surface and remain undetected by ToF-SIMS!

With a LN$_2$ sample cooling protocol, desorption is avoided and quantitative monitoring can be achieved (via W-TD-GCMS calibration)
ToF-SIMS analysis of VPD residues

ToF-SIMS analysis (left) at different locations within the droplet (right) shows its constant chemical composition.
VPD-TOF-SIMS vs. VPD-TXRF vs. VPD-ICPMS

Al (at/cm²) after correction

Oasis DNS

Fe (at/cm²)

Oasis DNS

Ca (at/cm²)

Oasis DNS

Aluminum (Calibration)

Iron

Calcium

VPD-TXRF results in lower values due to X-ray absorption in residue (0.2 – 1.0 µm thick)
Copper grainsize analysis with EBSD

EBSD diffraction pattern

Cu grainsize & orientation

blue is \{111\}, red = \{100\}
Strain Analysis with nm resolution: TEM-CBED

Si/Si(1-x)Gex/Si Epitaxial growth x=15%

Compressive biaxial stress: \( \sigma_{xx} = \sigma_{yy} = \sigma_0 = -1.1 \text{GPa} \)

Tetragonal distortion along z direction

FIB sample preparation
relaxation along [110] direction
Materials Analysis: Application Development

Strain Analysis with nm resolution: TEM-CBED

\[ \sigma_{xx} = \sigma_0 = -1.1 \text{ GPa} \]
\[ \sigma_{yy} = -0.2 \text{ GPa} \]

Holz Line broadening +

Finite element Modelling

Si/Si\textsubscript{(1-x)}Ge\textsubscript{x}/Si

Si

Si\textsubscript{0.85}Ge\textsubscript{0.15}

Si

\( t \)

\( z \)

\( y \)

\( x \)
Materials Analysis: Conclusions

• Materials analysis in latest technologies requires that more and more techniques become available (XRD, XRR, EBSD, Raman....) and that existing ones are more refined (SIMS, ToF-SIMS).

• Full wafer tools offer appreciable advantages but have its price!

• The materials analysis team provides analytical services but also actively develops a wide variety of applications and evaluates new metrology tools.
ELECTRICAL FAILURE ANALYSIS
Off-line Characterization

Without fault isolation
R&D support
Process development

With fault isolation
Yield loss analysis

Voltage Contrast
Test structure

OBIRCH
Test structure
Product

Bitmap
Memories

Physical characterization
FIB, SEM, TEM, EELS, AES, TOF-SIMS, XRR, XRD…
OBIRCH based analyses

Detection of resistive paths based on current changes

Detection sensitivity improves with higher laser power and higher current

But latest technology operates at lower V (lower $I_o$) and is more sensitive to laser induced damage…
YIELD Learning in 90 nm CMOS Technology

Physical Failure Pareto …

~ 20%: No defect found…

For 65 nm technology: > 30 % of defects not found
OBIRCH Limitations: Spatial Resolution

- OBIRCH spot surface ~ 1 µm²
- 65 nm elementary SRAM cell ~ 0.5 µm²
- In one OBIRCH spot: 12 transistors, 20 contacts,…

OBIRCH point superimposed on SRAM layout
OBIRCH Limitations: Spatial resolution

“Looking for a Needle in a Hay stack!”

Spatial resolution has to be improved
OBIRCH limitations: S/N ratio & laser power

Latest technologies require low laser power...

Lock-in amplifier is needed to improve sensitivity

\[ \partial I = -\left( \frac{I_o}{V_o} \right) \partial R \]
FA Limitations: SEM Spatial Resolution

FIB-SEM based BITMAP analysis

SEM Observation becomes delicate…!
FA Limitations: TEM Resolution is needed!

*Cobalt, Oxygen, Titanium*

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[Image of TEM analysis with labeled elements: Co, O, N, Titanium, Oxygen, Cobalt]
Electrical Failure Analysis: Conclusions

• Failure Analysis has been effective for 120 and 90 nm technologies but is less effective for 65 nm technology.

• The two main limitations are
  – Fault isolation inaccuracy
  – limited SEM imaging resolution

• New developments are definitely required
  – Improved OBIRCH, or complementary techniques
  – Software based Fault Diagnosis methods to identify faulty nets or cells
  – 3-D Tomography, TEM based EFA
CONCLUSIONS & PERSPECTIVES

• With the increase of technology complexity, also the need for adequate physical characterization support increases.

Many challenging development tasks are ahead of us!

• TEM microscopy and appropriate sample preparation techniques will be a focal point for the years to come.

• Several ‘Lab’ techniques will have to transform into ‘Fab’ techniques for in-line defectivity monitoring and metrology.

• The FA community needs to re-think strategy and to come up with new or smarter techniques and methodologies to narrow the gap that starts to exist between what is needed and what is available for effective failure analysis on most advanced technologies.
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