The Role of Wet Cleans in Semiconductor Process Development & High Volume Manufacturing Costs

Akshey Sehgal

Fab 8 Advanced Technical Development
Malta, NY
Doing it Right the First Time:

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<td>It takes a Village…</td>
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<td>Making it Happen</td>
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Effects of Wet Cleans on:
Advanced Node Technology Development & High Volume Manufacturing Costs
• Defects, Contamination all affect Yield

• Yield controls profit/ loss

• Fishbone construction
  • Partial list of all possibilities with quantified examples
  • Examples can be taken from every module of semiconductor manufacturing
  • Cost improvements come from
    • † yield
    • † efficiency
Upstream Processing
- RMG Defects from Junctions: As Implant, SPCR Dep

Now Important Cleans
- BS and Bevel

 Impossible Challenge
- BEOL TiN Metal
- Hardmask Removal

Repeat Processing
- FEOL SPM Cleans

Using process to overcome tool limitations
- Extra Pattern Defect Removal
BEOL Wet Cleans: Metal Hardmask Removal

- **TiN HM Removal**
  - *Wet clean has to remove TiN hardmask but not attack the TiN in the contact glue layer*
    - Both are simultaneously exposed to the same chemistry
    - TiN liner surface is vulnerable as surface tension and gravity will pull chemistry into recesses

Wet chemistry compatibility to dielectric stack critical

Low k stack

Nitride

W or Co

TiN liner

W or Co

Post Via Etch

TiN Wet Removal

Contact and TiN liner exposed

Post Via Clean

W or Co

TiN liner
**Hammer Test**
- Expose wafer to TiN MHM chemistry when there is no TiN MHM on wafer surface
- Only TiN exposed to chemistry is the TiN liner in the contact liner

**Purpose**
- Determine if TiN MHM removal chemistry attacks TiN liner in Contact

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**Contact CMP (MOL)**

**TiN MHM Removal (BEOL)**

**TEM**

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**TiN MHM Removal Chemical**

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**Impossible Challenge**

April 9, 2018
RESULTS

• Chemistry does not attack TiN liner in isolated contacts and in seas of contact

• Repeated test show the same result (verified with elemental TEM on repeated wafers)

• Yield ↑ compared to POR formulation that did attack TiN liner in the same test
Materials
• R&D must deliver technologies which meet customer performance expectations

• Innovations are implemented when value of the improvement > its cost
Lots of new materials in semiconductor grade purity and,

- Shrinking dimensions = killer defect size $\downarrow$ = higher purity requirements

For advanced technology development, materials cost are $\uparrow$
3 Rs and cheaper substitutes are the only way to ↓ materials cost

- Advanced technology development and,
- High volume manufacturing
**Sulfuric Acid Cycle in Wet Cleans**

**REDUCE**
- SPM dispense time
- SPM line flushing (new lot and idle time)
- Replace with DIO$_3$ wherever possible

**RECLAIM & REUSE**
- SPM reclaim
- Optimize SPM drain time († DIW rinses going into SPM collection tank)
- Drain delay times at the tool were optimized to reduce water and peroxide going into acid drain, thereby increasing acid concentration

Total SPM reduction from 3Rs = 58%
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GLOBALFOUNDRIES Technologies

Broad and differentiated product offerings

**Mainstream**
- 180nm to 40nm
- 200mm, 300mm wafers
- Mixed-technology solutions based on proven processes
- Analog/Mixed-Signal, RF/mmWave, high-voltage (power management)
- RF CMOS, embedded memory, display drivers, MEMS

**Leading Edge**
- FDX™ Technology
  - Industry’s first FD-SOI roadmap
  - Ideal for IoT, mainstream mobile, RF, and power-efficient SoCs
- FinFET Technology
  - Industry roadmap for performance and density
  - Ideal for High-end Mobile, Servers, Graphics and Networking
- 28nm HKMG/Poly-Si
  - Industry leader, over 1 million wafers shipped
- Driving rapid migration to RF and embedded memory on leading-edge platforms
HVM LEARNING:
Defect Traceability at Wafer Level is too late
Need to define path towards negative mean time to detect (nMTTD)

Increased number of elements with potential for variations and defectivity contributions

Increased Impact of undetected variations or controls

Wafer Level
Die Yield, # of Excursion

System Level
Equipment, Materials & Processes

Sub-System Level
Components, Parts & Raw materials

Sub-Component Level
Part Materials, Fundamental Chemistries, Formulations

Line of defense & Industry Standards at each level
Contribution of Sub-component Abnormality to Wafer Defects

Significant loss of productivity and efficiency

✓ CHEMICAL SUPPLIER
✓ ISO-TANKER DELIVERY
✓ BULK TANK
✓ FACTORY DISTRIBUTION
✓ WET CHEMICAL
✗ DEFECT DETECTION @WAFER

✓ ISO-TANK HEALTH & SUPPLIER

ROOT CAUSE LINKED SUB COMPONENT SUPPLIER (SEAL & MATERIALS issue)

30-35 nm Particles

April 9, 2018
Wafer Failures While All Specs Are Met: Impact from Raw Material Variations

- Metal contamination and intermittent failures originating from variations in sub-supplier raw materials (Root cause analysis)

- 10x ↓ in Ca in raw material
  = 5x ↓ in Ca on wafer surface

- For sub 1x nm nodes
  - Need visibility into sub-supplier chain and quality control
  - Metal contamination in raw materials in ppt level (measure, report and control)

**Formulation Produced Time Period 1**

<table>
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<tr>
<th>Component</th>
<th>Period 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>&lt; 1 ppt</td>
<td>&lt; 18 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Ca</td>
<td>&lt; 4 ppt</td>
<td>3750 ppt</td>
<td>&lt; 32 ppt</td>
</tr>
<tr>
<td>Mg</td>
<td>&lt; 1 ppt</td>
<td>80 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt; 1 ppt</td>
<td>&lt; 25 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Zn</td>
<td>&lt; 1 ppt</td>
<td>850 ppt</td>
<td>24 ppt</td>
</tr>
</tbody>
</table>

**Formulation Produced Time Period 2**

<table>
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<tr>
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<th>Component 2</th>
<th>Component 3</th>
</tr>
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<tr>
<td>Component A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>&lt; 1 ppt</td>
<td>&lt; 5 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Ca</td>
<td>&lt; 4 ppt</td>
<td>350 ppt</td>
<td>&lt; 32 ppt</td>
</tr>
<tr>
<td>Mg</td>
<td>&lt; 1 ppt</td>
<td>&lt; 25 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt; 1 ppt</td>
<td>&lt; 25 ppt</td>
<td>&lt; 16 ppt</td>
</tr>
<tr>
<td>Zn</td>
<td>&lt; 1 ppt</td>
<td>&lt; 50 ppt</td>
<td>24 ppt</td>
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It takes a Village Global effort to drive zero excursion zero defect mission

- Minimize Process VARIATIONS
- TRACEABILITY-on-the-GO
- Standardization
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Journey to Excellence

- All GLOBALFOUNDRIES Inc. customers need us to excel in
  - Manufacturing Capacity & Capability,
  - Technology Leadership and,
  - Customer Service

- How do you deliver customer service in wet cleans and improve cost (↓ CoO, ↑ asset utilization etc.)?
P Buried Layer Defects

Problem in Complimentary BiCMOS technology
- Defects in P Buried Layer (PBL) seen after optical inspection (0.1 µm deep, few µm across)
- Electrical testing co-related these defects to PNP array current leakage

From Akshey Sehgal et al. UCPSS 2010
P Buried Layer Defects

- **ROOT CAUSE**
  Mo is unintentionally co-implanted with the \((^{11}\text{B}^{19}\text{F}_2)^+\) implant which has the same mass to charge ratio of 49 as the doubly ionized \(^{98}\text{Mo}^{2+}\). PBL defectivity directly proportional to BF\(_2\) implant dose.

- **HVM FIX**
  Change to a Tungsten/ W source for the BF\(_2\) implant. W does not have a species with a mass to charge ratio of 49 and is therefore, not co-implanted into the wafer.
Fix Problem “Wet Cleans” Created

- Need to produce wafers while PBL implant target change is qualified

- Found that for PBL Oxide Strip, BOE shows PBL defects and 100:1 dHF does NOT show PBL defects

<table>
<thead>
<tr>
<th>PBL Ox Etchant</th>
<th>Time in F Bath</th>
<th>PNP Transistor Array Leakage</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:1 BOE</td>
<td>Couple of min</td>
<td>Yes</td>
<td>Mo left on wafer surface after PBL Ox removal</td>
</tr>
<tr>
<td>100:1 HF</td>
<td>Couple of hours</td>
<td>No</td>
<td>No Mo left on wafer surface after PBL Ox removal</td>
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- Since Mo is already present in both wafers coming into PBL Ox removal, how is F modulating PBL defectivity?

- Impractical HVM solution to process lots for couple of hours in 100:1 dHF bath
PBL Implant performed with W source

To fix far too long PBL oxide removal wet clean

- HVM step done with removing most of PBL oxide in BOE bath and then transferred to 100:1 HF bath

1st Step:
5:1 BOE removes 90% of PBL oxide

2nd Step:
Transfer to 100:1 HF bath to remove remainder 10% of PBL oxide
Mo defects only exposed to 100:1 HF

Using this 2 step wet cleans in HVM, process time is 1/3rd of time needed in 100:1 HF bath only
Review of the Geology literature revealed that silicon and molybdenum form a water soluble silicomolybdate complex.

Fluoride ions interfere with the formation of the silicomolybdate complex.

<table>
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<tr>
<th>PBL Ox Etchant</th>
<th>F Content</th>
<th>Silicomolybdate Complex</th>
<th>Mo Left on Wafer Surface</th>
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</thead>
<tbody>
<tr>
<td>5:1 BOE</td>
<td>24.544 wt%</td>
<td>Does NOT form</td>
<td>Yes Causes PNP array leakage</td>
</tr>
<tr>
<td>100:1 HF</td>
<td>0.568 wt%</td>
<td>Forms</td>
<td>No Does NOT cause PNP array leakage</td>
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Modeling the PBL Oxide Strip: Si-Mo-H₂O

Si-Mo-F-H₂O Systems

Silicomolybdate complexes

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Journey to Excellence: Customer Service

• Solving problems “created by wet cleans”
  - You are not done until ALL stakeholders say you are done and,
  - OWN the problem and delivering an effective HVM solution

• Customer service in wet cleans also involves:
  - Solving other people’s problem(s) (next slide)
**BACKGROUND:**

- 2x nm transferred technology to GLOBALFOUNDRIES Fab 8 in Malta used a cleaning chemical *not* used in Fab 8

- Chemistry is:
  - Only used for 1 cleaning step in MOL among multiple technology nodes being scaled up in Malta
  - Completing CE transfer and then eliminating the chemical from the 2x nm route = 8 months and a $ few million

**Problem Statement:**

- Is it possible to eliminate one of a kind (OOAK) cleaning chemistry?
- Possible to replace it with a new chemistry that
  - Meets process objectives?
  - EHS friendly?
  - with low CoO?
Run splits at the OOAK cleaning step (pathfinding fab)

Characterize etch residues produced
Fundamental analysis of cleaning ability of OOAK clean and new clean

Run split with new clean (vs. OOAK clean)
If good, repeat
If still good after repeat, perform EHS impact and cost analysis

If good, permanent change of 2x nm Route
**OOAK Clean (What):**
Contact Wet Clean in MOL

*HVM Requirements:*
- Complete removal of contact etch residue
- Exposed Al, RMG metals, W, OX and NIT unattacked

Picture shows CB, missing W and residue blocking fill

*Area at M1*
OOAK Clean *(What):* Characterizing the Etch Residue it Needs to Remove

N, O, Ti, F were mapped in defect

5 A nominal EELS probe was used

*O & F residue seen above TiN liner*

* OOAK clean is not removing F containing SWP (sidewall polymer)
In OOAK chemistry solution both Al and W dissolve into soluble hydroxides = RMG attack

No Pourbaix diagram for TiN found in literature so need to construct from first principles

- TiF$_x$ residues are NOT removed by OOAK chemistry

Pourbaix diagram shown above are for M-H$_2$O system. We need Pourbaix diagrams for M-F-H$_2$O system
Multiple element Pourbaix diagram was constructed

It identified a process space that met all criteria
- New cleaning chemistry formulated from chemicals already available in Fab 8
- EHS friendly & low CoO criteria were met (formulated onsite)
- New chemistry, skipping OOAK Clean, removed all residue without attacking any exposed materials

Benefits:
- Lower \( R_{ON} \) (x \( \rightarrow \) 0.7x \( \Omega \cdot \mu m \))
- NFET \( I_{eff} \) @ \( I_{off} \) improved \( \sim 7\% \)
- PFET \( I_{eff} \) @ \( I_{off} \) improved \( \sim 3\% \)
- Ring Oscillator yield increased with addition of new chemical

Process flow permanently changed to include new clean
OOAK Clean (What): Cost Impact

- CapEx Costs (Dedicated wet clean tool and cabinets)
- Chemical Costs (CDU, BCDS, Consumption)
- Facilities Costs (Drains, Waste treatment etc.)
- Throughput Improvement from New Chemistry

Total Cost = Capital Spending + Chemical Spending + Facilities Cost + …

<table>
<thead>
<tr>
<th>Item</th>
<th>Without OOAK</th>
<th>Comment</th>
</tr>
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<tbody>
<tr>
<td>Total Savings to date</td>
<td>~ US $ 28 Million</td>
<td>New wet clean replaced 2 back to back wet cleans</td>
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Not doing Copy Exact gave superior process and saved $28 Million
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**Common Theme in All Sections:**
- OWN the problem *and* the solution
- Well defined problem statement
- Use 1st principles to solve problems
- Attention to details
- Great team (internal and externally)
WHAT:

• All sectors are improved/ enabled by semiconductors delivering growth and productivity
• Wet Cleaning and surface preparation are critical for IC manufacturing

WHY Wet Cleans:

• Enable fast decision making and action taking by “doing it right the first time”
• To increase your odds of being right:
  • Work cooperatively globally,
  • Learn from experts on a daily basis and,
  • Use personal knowledge to serve (internal & external) customers’ needs
Acknowledgements

Grateful thanks to GLOBALFOUNDRIES colleagues and former company colleagues in

- Wet Cleans, Metrology and Defect Inspection
- Integration, Device and, TCAD
Questions?