Challenges and Opportunities: Sub-10nm Generation Patterning Materials

Wang Yueh, Intel Corporation

Acknowledgements: Intel EUV teams

Oct. 29, 2014
Outline

- Current Sub-10nm Patterning Strategies
- ArF immersion vs EUV
- EUV Approaches:
  - Traditional Resists
  - Novel Resists
  - Ancillary Materials
- HVM Materials Requirement
- Summary
What Might Work For Sub-10nm?

E-beam?

EUV?

ArFi?

DSA?
2-D Lithography: ArFi vs. EUV

- EUV: more attractive since the process is much simpler

- ArFi: typically requires a multiple patterning process in conjunction with a complex *cocktail* of material layers, which may include:
  - Shrinkage (vias)/Slimming (lines) materials
  - Negative tone images (NTI)
  - Others

Mark Phillips, SPIE 2014
**ArF for More “Moore”**  
**More Materials = More Cost**

From 45nm node (dry) to 14nm node (wet) & beyond

<table>
<thead>
<tr>
<th>Dry/UL 45nm</th>
<th>Wet/Dual UL 32nm</th>
<th>DP/Dual UL 22nm</th>
<th>MP/Dual UL/NTI/SM 14nm &amp; beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>$</td>
<td>$$$</td>
<td>$$$$$$$</td>
</tr>
</tbody>
</table>

From a single Hamburger to Multiple Double Cheese Hamburger, plus drinks, wine and ice cream
ArFi For Sub-10nm Nodes

• ArFi has been successfully implemented for several generations, but complexity is increasing

• Multi-patterning processing is possible, but not simple
  – Need to balance number of patterning steps and complexity of the stack (UL/resists/topcoats/shrink materials) to optimize for cost and technology
  – Defect challenges become increasingly difficult due to multiple patterning steps, stack complexity, and smaller features – yield focus
Current EUV Approaches

- **Traditional Resists:**
  - Optimization of existing formulations – PAGs, polymers, quenchers

- **Novel Resists:**
  - PAG bound polymers
  - Molecular glass
  - Negative tone resists
  - Negative tone Image resists
  - Absorbance enhanced materials: Nano-Particles, etc
  - Metal oxide Non-CAR

- **Ancillary Materials:**
  - DDRM: Dry Develop Rinse Material
  - Rinse materials
  - Topcoat
Traditional EUV CAR Resist

- Continuous progress on resolution, but still need to improve the sensitivity and LWR

ICPST 2014, Gstrein et al
Improvement of CAR

Formulation optimization gets us part of the way however…. *Can we extend below 12nm HP??*
Can Quencher Help?

Resist A = High resolution resist
Resist B = 4X quencher loading of Resist A

- Infinite quencher ≠ gain in resolution
- Need contrast enhancement through Novel polymers and PAGs
Current EUV Approaches

- **Traditional Resists**
  - Optimization of existing formulations: PAG, Polymers. & Quenchers

- **Novel Resists**
  - PAG bound Polymers
  - Molecular Glass
  - Negative tone resists
  - Negative tone Image resists
  - Absorbance enhanced additives: Nano-Particles, etc
  - Metal oxide Non-CAR

- **Ancillary Materials**
  - DDRP
  - Rinse
  - Topcoat
PAG Bound Polymer Resists

Better acid diffusion control and PAG distribution in the film

EUV MET

Early PAG Bound

Evolution PAG Bound

Low sensitivity Advanced PAG Bound

26nm

LWR 6.4nm

10.0mJ/cm²

LWR 4.5nm

13.8mJ/cm²

LWR 2.5nm

28.0mJ/cm²

24nm

O

O

R

S

O

S

O

S

O

S

R

SO۳⁻

S⁺

SO۳⁻

S⁺

Better acid diffusion control and PAG distribution in the film
Continuous Improvement
PAG Bound Polymer Resists

Can it extend to sub-10nm HP?
Molecular Glass Negative Tone EUV

- Molecular glass resists are expected to have the better LWR
- Negative tone resists on DF mask performance is better
- Combination of these two concepts, how far we can push?

A: 22nm HP, Film thickness: 40nm
Albany-MET 0.3NA,
Negative Tone Image EUV Resist

PR thick. 40nm, PSI IL

16nm L/S

E = 38.3 mJ/cm²

16nm

20nm

18nm

16nm

15nm

14nm

13nm

NTI-CAR, based on conventional resist system
NTI Resist for Narrow Trench

PR thick. 45nm, imec NXE:3100 NA 0.25, Conv. (σ 0.51), CD on mask = 28 nm

**NTI process looks promising on trench application.**

**However, the cost of NTI (organic solvents) process is more expensive than PTI (TMAH) process**
Nano-Particle Resists

Transition metals have the advantages:

- Increasing EUV absorbance
- EUV Absorbance: Hf > Ti > Zr
- High etch resistance

HfO$_2$-methacrylate
30 nm HP
16.5 mJ/cm$^2$

ICPST 2014, Gstrein et al
NP-EUV With & Without PAG

R = MAA or BZA

Dose = 38 mJ
BMET, dipole illumination

28 nm
26 nm
24 nm
22 nm

With PAG

24 nm
22 nm
20 nm
19 nm

Without PAG

ICPST 2014, Gstrein et al

PAG not needed for patterning
NP-Non-CAR Improvement

NP EUV Key Challenges
- Shelf life
- Undesirable metal contamination
- Filter out?? During both manufacturing and at point of use (track)
CAR vs. Non-CAR

Source: Paul Scherrer Institute, SPIE 2013

- Non-CAR showed Sub-10nm resolution, however the sensitivity was extremely high.
New Metal Oxide Non-CAR: Better Sensitivity

- Non-CAR key challenges:
  - Higher Sensitivity
  - Longer Shelf Life
  - Defect Reduction?
Current EUV Approaches

- **Traditional Resists**
  - Optimization of existing formulations: PAG, Polymers. & Quenchers

- **Novel Resists**
  - PAG bound Polymers
  - Molecular Glass
  - Negative tone resists
  - Negative tone Image resists
  - Absorbance enhanced additives: Nano-Particles, etc
  - Metal oxide Non-CAR

- **Ancillary Materials**
  - DDRP
  - Rinse
  - Topcoat
About DDR process

Ref. : Conventional process

Exposure

Mask → PR

PEB

Development & Rinse & Spin dry

Pattern collapse

Capillary force...

DDR process : Dry Development Rinse process

Exposure

Mask → PR

PEB

Development & Rinse (No spin dry)

Dispense DDRM

Replacement by DDRM

No capillary force!

DDRMI (Dry Development Rinse Material)

Spin dry & Bake

Etch back

Dry etching

No pattern collapse!
Higher aspect ratio!

Key Process
Resolution Enhancement: DDRP

- hp 19nm: Pinching
- hp 18nm: Collapse
- hp 17nm: No pattern

Ref. PR pattern

CD-SEM

Pinching

CD-SEM

Collapse

CD-SEM

No pattern

DDRPR

X-SEM

OK

X-SEM

OK

X-SEM

Resolved
Line Collapse Mitigation with DDRM

- Promising process
- Reverse the images
- Can this be used for special applications?

ICPST 2014, Gstrein et al,
## EUV Rinse: FIRM Process

<table>
<thead>
<tr>
<th></th>
<th>19nm</th>
<th>DIW (ref.)</th>
<th>Extreme™ 10</th>
<th>Extreme™ A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution limit (nm)</td>
<td>17.6</td>
<td>17.2</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>Delta CD from DIW (nm)</td>
<td>NA</td>
<td>1.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>LWR (nm)</td>
<td>4.89</td>
<td>4.35</td>
<td>4.91</td>
<td></td>
</tr>
</tbody>
</table>

**Process window**

- **Available:**
  - 3 for DIW (ref.)
  - 12 for Extreme™ 10
  - 17 for Extreme™ A

---

**SEM image setting (Magnification)**

- **Previous:** X: 300K, Y: 300K
- **Current:** X: 300K, Y: 53K

<table>
<thead>
<tr>
<th>No collapse</th>
<th>Unavailable Pattern (collapse)</th>
<th>No collapse</th>
<th>Unavailable Pattern (collapse)</th>
</tr>
</thead>
</table>

**Notes:**
- No collapses
- Not available pattern: collapse, no resolution, melt
Topcoat for OoB & Outgassing

**OoB** (160-300nm broad band, 20% of EUV)

- **EUV**
- **PR**
- **Sub.**

**OoB protection**

<table>
<thead>
<tr>
<th>Dose</th>
<th>LWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7mJ/cm²</td>
<td>6.32nm</td>
</tr>
<tr>
<td>26.8mJ/cm²</td>
<td>4.10nm</td>
</tr>
</tbody>
</table>

**Bad**

- w/o OBPL
- w/ OBPL (10nm)
- w/ OBPL (30nm)

**Good**

- w/ OBPL

**Outgassing Protection**

- EUV
- PR
- Sub.

**Suppress the outgassing !!**

- Carbon contamination thickness (nm)
  - 6.74nm
  - 2.56nm
  - 0.01nm

- Carbon contamination thickness (nm)
EUV For Sub-10nm Nodes

- Overall COO will be the key concern, including,
  - Tools: source power, uptime, etc
  - Masks: defect-free reticles, pellicle readiness, etc
  - Resists: RLS, outgassing, etc

- Fine tuned traditional resists may be not able to meet the RLS requirements

- Novel materials/processes are needed, however, no outstanding winners yet

- Cocktail processes may be needed

- Novel materials integration challenges

- Additional out of boxes ideas??
Summary: HVM Requirements
Sub-10nm Generation Materials

C Q A T: For HVM End Users

C: Cost

Q: Quality

A: Availability

T: Technology
Cost is a significant issue

- EUV Cost Drivers
  • Long term R&D investments in advance of implementation
  • Equipment capability and throughput

- ArF immersion Cost Drivers
  • MP and “cocktail” stacks $\rightarrow$ both # materials and consumption increases
  • Defect reduction focus on each pass and each material
Aggressive Excursion Prevention

• Never ending drive on defect reduction
• Not seen ≠ not existent
• Tighter material SPECS are expected across the board: defects, metal contamination, particles, impurities, etc.
• Characterization of material micro-structures to avoid batch to batch variations → advanced metrology
• Advanced metrology tools are required

- EUV: Appropriate exposure tools for quality control

- ArFi: Understanding interface interactions between underlayer, resist, topcoat, shrink materials, etc.
**Availability**

*Never Short of Materials*
- Supply chains health is critical
- No Batch to Batch variations
- Faster lead time for raw materials and final goods

- EUV
  - Reasonable shelf life for certain materials
  - Manufacturing challenges for some raw materials

- ArF immersion
  - Robust supply chains for “novel” raw materials
Novel Materials and Processes are Needed
- LWR is extremely important for smaller CD
- Defect-free is one of key successful factors
- Enable novel materials/processes for COO
- Out of the Box alternatives?

- EUV
  - Materials meet RLS trade-off

- ArF immersion
  - Complexity between UL/Resist/TC/SM/Solvents
Acknowledgement

- Intel CR/PTD EUV Team
- Materials Suppliers:
  - AZ
  - FFEM
  - IM
  - Inpria
  - JSR
  - NCI
  - Sumitomo
  - ShinEtsu
  - TOK
- IMEC, PSI, LBNL Sematech

Show me the best materials