EUVL Contamination Control: What Research and Development is Needed for HVM?

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Outline

• Introduction

• Source Contamination
  • Damage Mechanism
  • Ion and Neutral Debris measurement
  • Erosion and life time prediction

• Collector Optics Contamination
  • Cleaning of Sn by RIE
  • Cleaning by Combining Heating and Secondary Plasma

• Projection Optics and Spectral Purity Filter

• Particle Contamination of Mask and Wafer
  • PACE cleaning of nano particles

• Line Edge Roughness

• Research and Development Need for HVM

• Acknowledgements
EUV Lithography

Uses light with a very small wavelength (13.5 nm) from a Extreme Ultra Violet Region of the light spectrum to transfer images from mask onto silicon wafer.

General lithography technique

- Silicon is the traditional substrate
- Mask contains the circuit pattern
- Light is directed onto a mask
- Light goes through the mask and through series of optical lenses which shrinks the image
- The small image is then projected onto wafer
- Wafer is covered with light-sensitive, liquid plastic called photoresist
- Light hardens the photoresist that is not covered with mask
- Photoresist that is not exposed to light can be chemically washed away, leaving the hardened photoresist and exposed silicon wafer
Introduction

• Moore’s law is reaching its limit.

Moore’s law: The number of transistors doubles approximately every two years [1].

• Good guideline to develop faster and denser chip but can’t continue forever.
• No exponential is forever – Moore.
• The smallest feature size today is 45 nm. We have another 10 to 20 years to reach the fundamental limit.

Light wavelength- The Key

Feature size scaling faster than wavelength reduction

R = k₁ \frac{\lambda}{NA}

- \lambda: Exposure Wavelength
- NA: Numerical Aperture
- \(k₁\): Constant depends on Resist Materials and Exposure Conditions

- Moore’s law has been driven by lithography
- The shorter the wavelength, the more transistors can be printed.

Courtesy: Intel
Integrated EUVL system

The entire integrated system is considered: source, collector, possible spectral purity filter, projection optics, mask, illuminator optics and wafer.
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Damage mechanism
Debris from the plasma source is the critical issue:

- Fast ions generated in the pinch can lead to significant collector erosion.
- Electrode materials generated during the plasma pinch from surrounding surfaces.
- Condensable metal vapor from advanced fuels (Sn or Li).
- Chemical interactions between collector mirror and debris (Sn or Li interactions).
- Degradation at elevated temperatures of because of the enhanced thermal interdiffusion of the high and low index materials within the mirror structure.

Ion debris measurement

XTREME Commercial EUV Emission Device (XCEED)

Electrostatic Spherical Sector Ion Energy Analyzer (ESA)

Experimental Set-up for ESA Calibration

Ions are discriminated based on energy-to-charge ratio

The spherical sectors are charged to equal voltages of opposite signs

The electric field created inside the device, turns ions by 160°, where they impact the micro-channel plates

ESA is calibrated using an Ion Gun and a Faraday Cup

Debris mitigation – Buffer gas

- Collimated Debris Tool/Buffer Gas
  - Designed by XTREME Technologies
  - Similar to collimator used in CVD/PVD processes

Buffer gas flow dramatically reduces energetic ion flux when the highest gas pressures are inside a foil trap so that the gas scattering deflects the ions into the foils.

Debris Mitigation comes at the cost of decreased light intensity


Electric field ion mitigation

Debris Mitigation Tool

Decrease by a factor of 3.75 for 4 keV Xe$^+$ ions using electric field post-foil-trap mitigation technique

Decrease by a factor of 88 for 4 keV Xe$^{2+}$ ions using electric field post-foil-trap mitigation technique
Ion energy reduction with $\text{H}_2$ (INERT)

By adding a small amount of lower-mass fuel (like hydrogen) the pinch expansion parameters are changed such that the heavy ions are not accelerated to the same energies. This works independent of collector type.

Is the Debris Problem Solved?

- All we have to do is measure the EUV output and the ion energy spectra with the debris mitigation systems in place for any system and we can see if it works. Right?
- No. Many debris mitigation systems may just neutralize the ions and not alter their energy.
- Also, low-energy neutrals, all the way down to thermal, can cause deposition and therefore also degrade reflectivity. In addition there seem to be other effects too.....

<table>
<thead>
<tr>
<th>Specie</th>
<th>Predicted Time (us)</th>
<th>Actual Time (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe²⁺, Si⁺</td>
<td>11.04, 11.07</td>
<td>11.15</td>
</tr>
<tr>
<td>Ni²⁺</td>
<td>11.32</td>
<td>11.31</td>
</tr>
<tr>
<td>Xe³⁺</td>
<td>11.97</td>
<td>11.87</td>
</tr>
<tr>
<td>Xe⁴⁺</td>
<td>13.82</td>
<td>13.77</td>
</tr>
<tr>
<td>Fe⁺</td>
<td>15.61</td>
<td>15.33</td>
</tr>
<tr>
<td>Ni⁺</td>
<td>16.00</td>
<td>15.80</td>
</tr>
<tr>
<td>Xe²⁺</td>
<td>16.93</td>
<td>16.93</td>
</tr>
<tr>
<td>Xe⁺</td>
<td>23.94</td>
<td>23.59</td>
</tr>
</tbody>
</table>

Xe⁸⁺ to Xe¹⁰⁺ radiates

Recombination (and acceleration) occurs during expansion

We see Xe⁴⁺, Xe³⁺, Xe²⁺, Xe⁺

Shouldn’t Xe⁰ be there too?
Neutral Particle Detection

Using micro-channel plates similar to those used in the ESA tool, detect neutral particles by diverting ions from the beam before allowing the remaining particles to impact. ESA spherical plates are used to divert ions.

The Neutral Detector (ND) MCPs can be calibrated in a way similar to that for the calibration of the ICE machines.
Energy Spectra

Calibrated, measured, total, ions and neutral debris with no buffer gas

Ion, Neutral, and Total Debris Energy Characterization

0% Buffer Gas

Low-energy “residual” ion peak

Huge energetic neutral spectra at slightly lower energies
Neutral Particle Mitigation

- The Neutral spectra was taken with different rates of buffer gas flow
- A strong mitigation effect is seen with increasing flow

Notice growing peak at low energies
What problems will these energetic ions and neutrals cause?

Reflectivity degradation from collector optics is an effect of debris interaction with collector system

- Sputtering will occur, destroying multilayers, or roughening grazing incident collectors
- Energy flux to the surfaces can promote carbon, oxygen contamination
How the reflectivity changes with number of bi-layers in a multi-layer mirror?

**Multi-layer Reflectivity @ 5 degrees from Normal**

- Reflectivity vs. Number of Bi-layers

  - **10% reflectivity loss**
  - **Series 1**

  - Number of bi-layers in order to maintain the maximum reflectivity (73%) = 50
  - Maximum tolerable erosion = 25 bi-layers (10% reflectivity loss)

How many shots can be made before the collector loses 10%?

An estimate for this can be made using our ESA analyzed ion debris spectra.
SEM was performed to measure erosion for eight samples. Erosion ranges from 10-50 nm for different materials.

### Measured Erosion (nm)

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured erosion (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Au</td>
<td>54</td>
</tr>
<tr>
<td>Mo</td>
<td>10</td>
</tr>
<tr>
<td>Si</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Si/Mo MLM</td>
<td>13</td>
</tr>
<tr>
<td>Pd</td>
<td>20</td>
</tr>
<tr>
<td>Ru</td>
<td>delamination</td>
</tr>
<tr>
<td>Au/Mo</td>
<td>11</td>
</tr>
</tbody>
</table>

### Predicted Erosion (nm)

<table>
<thead>
<tr>
<th>Material</th>
<th>Estimated erosion (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.1</td>
</tr>
<tr>
<td>Au</td>
<td>33</td>
</tr>
<tr>
<td>Mo</td>
<td>6.5</td>
</tr>
<tr>
<td>Si</td>
<td>5.8</td>
</tr>
<tr>
<td>Si/Mo MLM</td>
<td>8.5</td>
</tr>
<tr>
<td>Pd</td>
<td>18</td>
</tr>
<tr>
<td>Ru</td>
<td>11</td>
</tr>
<tr>
<td>Au/Mo</td>
<td>10</td>
</tr>
</tbody>
</table>

Erosion ranges from 10-50 nm for different materials.
Good agreement leads towards accelerated lifetime testing.

Confirming the relevance of ESA data.
Calculated results for Si/Mo

Sputtering yield calculation (SRIM) using SRIM from Ru, Si and Mo

<table>
<thead>
<tr>
<th>MLM Material</th>
<th>Xe (6keV @10°)</th>
<th>Sn (6keV @10°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruthenium</td>
<td>4.38</td>
<td>4.65</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.87</td>
<td>2.99</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.94</td>
<td>1.93</td>
</tr>
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Xe and Sn fluxes needed to erode one layer of Ru, Si and Mo

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<th>Xe (6keV @10°)</th>
<th>Sn (6keV @10°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruthenium</td>
<td>2.34x10^{15}</td>
<td>2.20x10^{15}</td>
</tr>
<tr>
<td>Silicon</td>
<td>6.17x10^{15}</td>
<td>5.93x10^{15}</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.06x10^{16}</td>
<td>1.07x10^{16}</td>
</tr>
</tbody>
</table>

Thus the fluence required to remove one bi-layer of Si/Mo is:

\[ 6.17 \times 10^{15} + 1.06 \times 10^{16} = 1.677 \times 10^{16} \text{ particles/cm}^2 \]

Lifetime prediction

How many shots are needed to **erode 25 bi-layers** with no mitigation?

*Flux measured* in experiment at 28 cm from the pinch = $1.87 \times 10^9$ ions/cm$^2$ pinch

*Particle fluence required* to erode 1 bi-layer from MLM = $1.677 \times 10^{16}$

Thus, $1.87 \times 10^9 \times \text{(no. of shots)} = 1.677 \times 10^{16}$

No. of shots $\sim 9 \times 10^6$

Thus a 9 million shot can erode a bi-layer
And 225 million shot can erode 25 bi-layer

----- can bring down the reflectivity by 10%

In HVM, if the source is operational at 10kHz, the mirror lifetime based on above calculation is predicted as 6 hours.

This is clearly unacceptable and shows why debris mitigation systems is important. Having a diagnostic tool such as ESA, one can keep track of debris system efficiency and therefore the life time of collector optics can be predicted.
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Contamination of Collector Optics

- Carbon contamination can happen anywhere
- Sn-DPP or LPP sources are welcomed because of their high conversion efficiency
- But Sn is a condensable fuel, which degrades the optics and reduces the mirror lifetime
  - Deposition takes place
  - Surface becomes rougher because erosion takes place simultaneously.
  - Off-normal events (mistakes) may occur

To improve the collector optics lifetime, Sn cleaning of the mirror surface is essential, especially if that process can correct roughness variations and mistakes too.
**RIE Experiment at CPMI**

*Reactive Ion Etching (RIE) Experiment*

Cleaning Sn debris on mirror using Ar/Cl₂ plasma etching to extend mirror life time

\[
\text{Sn} + 4\text{Cl}_2 \rightarrow \text{SnCl}_4 \quad T_b = 114 \text{ C}
\]

- “Galaxy” etching platform
- 2-turn internal ICP coil insulated with glass cloth tape
- Independent RF power for the chuck bias to control the ion bombardment energy
- Pumping systems including turbo molecular pump, cryogenic pump and dry pump for using corrosive halogen gas-Cl₂
- Computer controlled Mass Flow Controllers for Cl₂ and Ar
- Heater and cooling water for the samples
- RGA mounted to monitor the water vapor pressure
100 nm Sn was deposited on Ru. Sample was placed at the chuck. Chuck bias ~ -77 V. RF Power ~ 500 W. Pressure ~ 10 mTorr. Ar/Cl₂ ~ 5 sccm/25 sccm. Process time ~ 5 min.

Sn is cleaned. Ru is not damaged.

AES Results

Cleaning Sn on collector mock up shells

Before Cleaning

After Cleaning

AES

XPS

SEM

Sn Peak

Ru Cl₃

Center for Plasma Material Interactions

http://starfire.ne.uiuc.edu
After 20 minute cleaning

- Eight samples (~2000 nm Sn) were loaded on the large size mock-up and
- Each sample was 6 cm apart from one another.
- After cleaning, two samples (L1 and L2) in large gap showed depth change enough to be measured by a profilometer. Most of Sn was removed.
- The rest of samples were not etched deep enough to be measured by a profilometer.
- However, L3, S1, and S2 showed visual change of the sample surface.
- N/D* indicates that we could not measure a depth change even though it was apparent that some kind of change occurred. N/D indicates no change either visually or measured with profilometry.
For the next step, we used Ru samples contaminated by a real Sn EUV source. While depositing Sn by EUV source, QCM read ~10nm deposition. Energetic implanted Sn will also be present.

Two samples were placed at L1 and L2 position.

Left figure shows the XPS survey scan of those samples before and after cleaning.

Sn peak intensity did decrease after cleaning but we still need to improve cleaning conditions (e.g. higher power with better matching) to completely remove Sn.
SCOPE Facility

Surface Cleaning of Optics by Plasma Exposure

- **Multifunctional device that is capable of:**
  - Creating low energy Li neutral debris
  - Measuring Li evaporation rates from collector optic.
  - Measuring Li sputter rates from collector optics.
  - Modeling in situ cleaning recipes for collector optics

- **System components**
  - Lithium magnetron
  - Lithium ion gun, 0-3 keV
  - Multi-use E-beam evaporator
  - Helicon plasma source
  - Heated and biasable sample holder and transfer system.
  - RF Compensated Langmuir probe
SCOPE - Results

• Innovative results show the functionality and ability for in situ cleaning of collector optics with a helium secondary plasma.

Deposition with Magnetron

Secondary He plasma alone

Heating to 400° C Alone

Heating and secondary He plasma


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Contamination of projection optics

In the absence of an ultra high vacuum environment the projection optics is exposed to water, hydrocarbons and other contaminants in the presence of EUV photons.

Carbon/Oxygen contamination

Cracking model

Hydrocarbons physisorbed

Oxides strongly absorb EUV photons

Radiation-induced processes

Lifetime of optics strongly depend on carbon contamination


Carbon contamination degrade the reflectivity of the optics and drop in throughput.

Spectral purity filter

- Reduce out-of band radiation
- Protect optics from debris, outgassing from the resist
- Barrier for EUV absorbing gases

Why won’t ever be able to use it:

- Energy flux will damage it
- Contamination of the surface
- Absorption of out-of band radiation cause temperature increase and resulted in cut down the flux of photons.
- Limited life time.
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Contamination of wafer and mask

• EUV Radiation induced carbon, oxygen contamination
  • Out gassing of photoresist
  • Residual hydrocarbon in chamber
  \[ \downarrow \]
  Reflectivity drop of ML mirrors
  Reduce life time

• Particle contamination
  \[ \downarrow \]
  Affect the printing pattern
Images obtained using the DEFCON analysis system at UIUC (laser scattering setup) allows for the ability to image the same position before and after PACE processing.

- No size limitation. No damage. Whole mask cleaned at once.

100% cleaning is possible
Cleaning of Cr Mask Blank

- 80 nm PSL deposited on Cr mask blank

This looks like 100% cleaning!
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With feature sizes shrinking to the nanometer scale, deformities in the trenches become more noticeable. This roughness is known as Line Edge Roughness (LER) or Line Width Roughness (LWR).

LER is caused by inhomogeneous photocatalysts in photoresist and varying light intensity. LER worsens as intensity of light is decreased.

LER causes inhomogeneity in etching and depositing steps that occur during microchip manufacturing, limiting chip size and reliability.
LER results

SEM pictures

Unprocessed sample 3σ LER of 12.3nm

Processed sample 3σ LER of 8.5nm
In conclusion: What research and development is needed for HVM

- Need more sensitive resist and/or more source power
- Need to develop an effective detector to measure debris at Intermediate Focus
- Need reliable cleaning technique for collector optics
- Potential mitigation techniques to reduce the reflectivity loss due to carbon and oxidation on projection optics and mask
- Need reliable technique to clean mask
Acknowledgements

- INTEL (Robert Bristol)
- USHIO
- XTREME
- CYMNER
- NIST
- MRL UIUC

Thank you for your attention