PAST

- The early years
- Carbon growth
- Clean vacuum
- DGL
- Mitigation (EToH/O$_2$)
- Cleaning with H*/H+
Control of debris production of laser plasma sources with high average XUV power

FOM-Institute for Plasma Physics Rijnhuizen, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands,
*Rutherford Appleton Laboratory, Chilton, Didcot, UK

SPIE Vol. 1848 Laser-Induced Damage in Optical Materials: 1992 / 517

Fig. 1. Deposition rate of clusters in vacuum and in He at sub-atmospheric pressure. The inset shows the experimental set-up.
CARBON GROWTH

- Was one of the showstopper for EUV lithography
  - Sources:
    - Residual gasses from vacuum
    - Resist outgassing
    - Impurities in gas supply
    - Greases etc. from moving parts

Graham et al., EUV contamination workshop 2003
CARBON GROWTH

- Scales with partial pressure and type of hydrocarbon, EUV intensity and EUV pulse shape

Reflected loss $\Delta R$ vs EUV power, using model CxHy at 1E-5 mbar (accelerated test)

H. Meiling et al, EUVL symposium 2006
The 5- and 10- minute exposures at 5 mTorr have the same rate.
Higher pressure acrylic acid contaminates at a higher rate.
CARBON GROWTH

- Reducing carbon growth:
  - Minimize residual hydrocarbons (Ultra Clean vacuum, grease free design)
  - Protect sensitive surfaces
  - Mitigation (oxidation, reduction)
  - Cleaning
ULTRA CLEAN VACUUM (UCV)

- One of the problems: Carbon contamination of EUV mirrors

Carbon growth:

\[ \text{C}_2\text{H}_2 + \text{EUV} \rightarrow \text{H}^+ \\
\text{H}^+ \rightarrow \text{H} \rightarrow \text{H}_2 \text{O} \rightarrow \text{O} \]

Oxidation:

\[ \text{H}_2\text{O} + \text{EUV} \rightarrow \text{O} \rightarrow \text{diffusion} \]

This happens at hydrocarbon pressures below 1E-12 mbar!

DIFERENCE BETWEEN ULTRA HIGH VACUUM AND ULTRA CLEAN VACUUM

<table>
<thead>
<tr>
<th></th>
<th>UHV</th>
<th>UCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pressure</td>
<td>Extremely low (e.g. &lt; 10^{-6} mbar)</td>
<td>Moderate (e.g. &lt; 10^{-1} mbar)</td>
</tr>
<tr>
<td>Specific components</td>
<td>Extremely low (e.g. &lt; 10^{-10} mbar)</td>
<td>Ultra low (e.g. &lt; 10^{-12} mbar)</td>
</tr>
</tbody>
</table>

Koster et al, AVS annual symposium 2014
Mitigation of surface contamination from resist outgassing in EUV lithography

B.M. Mertens\textsuperscript{a}, B. van der Zwan\textsuperscript{a}, P.W.H. de Jager\textsuperscript{a}, M. Leenders\textsuperscript{a}, H.G.C. Werij\textsuperscript{a}, J.P.H. Benschop\textsuperscript{b} and A.J.J. van Dijsseldonk\textsuperscript{b}

\textsuperscript{a}TNO Institute of Applied Physics, P.O. Box 155, 2600 AD Delft, The Netherlands
\textsuperscript{b}ASML, De Run 1110, 5503 LA Veldhoven, The Netherlands

One of the enablers for EUV Lithography. One of the reasons for ASML to start with EUV!
MITIGATION

**Optics lifetime/Carbon deposition Mitigation**

Carbon deposition on EUVL exposure tool optics degrades throughput and imaging quality. Mitigation method of carbon deposition has been developed.

- O$_2$ + O$_3$ is effective as the mitigation gas in the region of HVM Tool EUV intensity.

This experiment was performed as a collaboration work of Canon, Nikon and University of Hyogo.

Poster: OC-P06 T. Nakayama et al., Canon, NIKON, LASTI

**Suppression of carbon contamination**

- Cleaning rate with O$_2$ + EUV
- Contamination modeling

Contamination / cleaning modeling was established by using data obtained from experiment in SR facility.

Miyaki *et al.*, EUVL symposium 2010

Kawai *et al.*, EUVL symposium 2010
MITIGATION

- Heavy hydrocarbons disrupt process → slowly replace volatiles with non-volatiles
- Balancing very difficult

Prevention of oxidation:

**admission of EtOH** (Klebanoff et al)

- EtOH + EUV creates a void-free monolayer of carbon
- Surface now is hydrophobic, therefore strongly reduced H₂O-induced oxidation
- C-growth continues due to contamination hydrocarbons!

\[ \text{C}_2\text{H}_5\text{OH} + \text{EUV} \]

Balancing gas phase chemistry is the trick!

Koster et al, MNE 2001
CLEANING

In-Situ Cleaning Experiments Based on Carbon Volatilization Using Oxygen or Hydrogen

**Cleaning Strategy:**

Volatilization Reactions

- \( C + O \rightarrow CO \uparrow \)
- \( C + 2O \rightarrow CO_2 \uparrow \)
- \( xC + yH \rightarrow C_xH_y \uparrow \)

Generate Oxygen atoms with remote RF-discharge or Thermal Cracking over a hot tungsten filament. Expose in Line-Of-Sight Conditions.

• Samples: 100 Å Carbon on Si Wafer
  - Bare Si-capped Mo/Si optics
  - Bare Ru-capped Mo/Si optics

Determine Carbon Etch Rate

Determine “Overshoot” Risks to Optics

Post Evaluation of Samples:
- At-wavelength reflectivity
- Auger depth profiling

Cleaning of Carbon Contamination with Catalytic or Hot-Wire CVD Apparatus

Apply to atomic hydrogen cleaning of carbon contamination on Mo/Si multilayer to aim highly speedy and damage-less cleaning

Sample preparation:
- Mo/Si Multilayer sputtered on Si wafer
- Carbon deposited on Multilayer

Measurement:
- Surface carbon amount by XPS
- Carbon film thickness by optical system
- EUV reflectivity by reflectometer

This Work

Radical Formation by Heated Catlyzer (Hot-Wire Filament)
- No plasma damage
- Large-area homogeneous film formation
- High radical density (~10^{14}/cm^2)
- Resist can be removed.

EUV Contamination Workshop 2003

2004.11.2 EUV Symposium H. Ozumi

EUV Process Technology
CLEANING

- Shielded Microwave Induced Remote Plasma
- Hydrogen as active species for metal capping layer
- Oxygen for oxide capping layer

SMIRP Cleaning Results

Over-exposure of sample EUV multilayer mirror, equivalent to 11.6 nm C-removal:
- No reflectivity loss
- No degradation of capping layer
- No cross contamination found with XPS analysis

<table>
<thead>
<tr>
<th>Date</th>
<th>Pre (weeks)</th>
<th>Post (weeks)</th>
<th>Difference (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>R (%)</td>
<td>R (%)</td>
<td>ΔR</td>
</tr>
<tr>
<td>CTW06 (nm)</td>
<td>13,612</td>
<td>13,607</td>
<td>-0.005 nm</td>
</tr>
<tr>
<td>CTW09 (nm)</td>
<td>13,555</td>
<td>13,542</td>
<td>-0.013 nm</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>0.561</td>
<td>0.564</td>
<td>0.002 nm</td>
</tr>
<tr>
<td>SE peak (nm)</td>
<td>11.36</td>
<td>13.34</td>
<td>2.027 nm</td>
</tr>
</tbody>
</table>

Reflectivity is normalised!

Koster et al, EUVL 2009
CLEANING

Koster et al, SPIE 2012, 83220R

Plasma cleaning of TaN

7 min SEM exposure

Second 7 min SEM exposure

20 min plasma

20 min plasma

80 nm lines in 400 nm TaN, with approximately 2 nm C
Major showstopper for EUVL is solved

Optics lifetime for carbon contamination under control by clean vacuum and in-situ cleaning tools

Reticle contamination and lifetime still an issue

Only one working point where EUV intensity, CxHy pressure, O2 pressure are balanced. Otherwise either carbon growth or oxidation will occur

Surface coverage by light hydrocarbons is not stable. Light hydrocarbons will be replaced by heavy hydrocarbons over time
PRESENT

› Resist outgassing
› EBL0/1/2
› Collector lifetime
› Reticle lifetime
› Pellicle lifetime
RESIST OUTGASSING

- First proposal for resist testing by TNO/ASML/Carl Zeiss in 2006
- Procedure by ASML established in 2007

Before and after exposure → DR/R = -33%
→ Carbon spot mimics EUV beam shape
RESIST OUTGASSING

- Many sites invest in resist outgassing test set-ups according to ASML procedure
- Large differences between sites and excitation method (EUV or e-beam)
- 2015 ASML drops resist outgassing rate specifications
- New metal oxide resists evolve, contamination issues not known.
- 2017 IMEC to receive DGL membrane, enabling metal oxide resist testing

Sernatech outgas testing Round Robins
Organized by Karen Petrillo and Jaewoong Sohn, Sematech

Only sites 2 and 4 showed similar trends in Round Robin II
NIST values consistently lower than others in both Round Robin I & II

Tario et al, EUV workshop 2014, Maui
OPTICS LIFETIME @TNO

- Beamline at Bessy II
- Semi continuous EUV beam
- Established 2001
- Still operated by PTB
OPTICS LIFETIME @TNO

EBL established 2006
Xe source

EBL2 realized 2017
Sn source
EBL2 KEY PERFORMANCE

- Clean background environment to have full control of environmental conditions
- In tool surface analysis by XPS and imaging ellipsometry
  - EUV reflectometry will be added later
- Flexible system: custom samples, gases, geometries possible
- Accepts EUV reticles and returns them in NXE compatible state

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>&gt;1 W in 2% BW @ 13.5 nm (&quot;IB&quot;) (~10 W 10-20 nm)</td>
</tr>
<tr>
<td>Power density</td>
<td>&gt;1 W/mm² IB in focus</td>
</tr>
<tr>
<td>Spot size</td>
<td>1 – 30 mm diameter (power density scales)</td>
</tr>
<tr>
<td>Rep rate</td>
<td>1 Hz – 10 kHz (standard 3 kHz)</td>
</tr>
<tr>
<td>Sample size</td>
<td>Max 152x152x20 mm (reticle + pellicle possible)</td>
</tr>
<tr>
<td>Dose control</td>
<td>&lt;20 % in free running experiment</td>
</tr>
<tr>
<td>Uninterrupted exposure time</td>
<td>&gt;100 hours</td>
</tr>
</tbody>
</table>
Cymer increased lifetime of collector with increasing EUV powers

Cleaning of Sn in-situ shown (2014) by ASML

Collector lifetime extended with improved reflectivity

- Typical collector lifetime improved by factor 1.5 in 2016
- Data from 80W configuration in the field

- More details in afternoon session ASML presentation
- Bottom Line: expect significant improvement in system availability

Turkot et al, EUVL symposium 2016

PRESENT CONCLUSIONS

- Collector lifetime moving in the right direction
- Reticle defectivity almost up to HVM specifications but still a problem for HVM
- Pellicle is a must to ensure HVM production
FUTURE

- EUV induced plasma
- Surface chemistry
- Material/photon/ion interaction
- 1 kW EUV source
EUV INDUCED PLASMA

• Increasing powers and power densities will generate ions and radicals → self cleaning
• Ion energy can reach up to tens of eV (sputtering)
 MASK

- Bubble formation at high powers
- Damage mechanism similar to fusion technology?
- Collector lifetime at high powers?
- Pellicle needed for defectivity

**Mask - Lifetime**

After exposure of ~40,000 wafers, what happened at the mask?

Mask bulge is formed by hydrogen ion penetration and it will be prevented by improving blank fabrication process.

*Kim et al., SPIE 2016*
PELLICLE

- Much work already done
- How about lifetime? Increasing EUV powers → heating, warpage, pinholes
- Printing effects

NXE Pellicles are being mounted and used in scanners

Prototype pellicle on early integration mounting tooling

Fomework et al, EUVL workshop 2016
RESIST

- New formulations
- Nano particles
- Metal oxides

- DGL membrane to solve outgassing issues of metallic components into optics region

Improvements in resist performance towards EUV HVM
Oktay Yildirim et al, ASML, Proc. of SPIE Vol. 10143, 101430Q
Metal-oxide resist development needs to be expedited

Kim et al, SPIE 2016
1 KW EUV SOURCE

- Is a FEL an option?
  - Beam delivery and beam splitter
  - Reliability
  - Uptime
- How far can we stretch LPP sources?
  - Droplet rep rate
  - Laser rep rate
  - Conversion efficiency
  - Sn contamination

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More Powerful & Efficient EUV Source

Key components of a free-electron laser (FEL) EUV source

- SRF Accelerators
- Undulators
- EUV Optics
- EUV Scanners

<table>
<thead>
<tr>
<th>Item</th>
<th>Target</th>
<th>Motivation/Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>&gt;20 kW</td>
<td>Ten 1kW scanners (50% transport loss)</td>
</tr>
<tr>
<td>Availability</td>
<td>&gt;99%</td>
<td>Some redundant system hardware required</td>
</tr>
<tr>
<td>CoO</td>
<td>$250M CapEx, $20M OpEx</td>
<td>2x better than CoO for 10 LPP sources</td>
</tr>
<tr>
<td>General Configuration</td>
<td>Energy Recovery LINAC @ ~2K SASE Output</td>
<td>Maximize efficiency &amp; minimize cost</td>
</tr>
<tr>
<td>Timing</td>
<td>TBD</td>
<td>To intercept high-NA EUV scanner insertion</td>
</tr>
</tbody>
</table>


Wood et al, EUVL symposium 2016
CONCLUSION

- We are moving into HVM, with associated problems:
  - Reliability
  - Increasing EUV powers
- Contamination control went from simple carbon contamination to complex photon/material interaction
  - New cap layers needed?
  - Material research

- We are almost at the end of the tunnel and the light is getting brighter
ACKNOWLEDGEMENTS

Everybody working in the EUV community, without you this could not have happened

ASML | ZEISS | SAMSUNG | tsmc | CYMER | Canon

GLOBAL FOUNDRIES | intel | SEMATECH | NIST | SUNY POLYTECHNIC INSTITUTE

FOM | PTB | ASET | SEMATECH | NIKON
THANK YOU FOR YOUR ATTENTION

Take a look: TIME.TNO.NL