Overview of Lithography: Challenges and Metrologies

Harry J. Levinson
Progress in Lithography

• Progress in lithography has been the result of many advances.
  – Better lenses, resists, chemical-mechanical polishing (CMP), etc.

• The largest impacts have been made by changes in wavelength.

\[
g\text{-line} \rightarrow i\text{-line} \rightarrow \text{KrF} \rightarrow \text{ArF} \rightarrow \text{F}_2 \\
436 \text{ nm} \rightarrow 365 \text{ nm} \rightarrow 248 \text{ nm} \rightarrow 193 \text{ nm} \rightarrow 157 \text{ nm} \\
1 \mu\text{m} \quad \rightarrow \quad 360 \text{ nm}
\]
Shorter wavelengths

- Shorter wavelengths make a number of problems easier.
  - Improved depth-of-focus.
  - Smaller mask error factor.
  - Larger image log-slope.
    - Improves exposure latitude, sensitivity to resist thickness, and increases resist side-wall slope.

- We are running out of wavelengths.
Why are we running out of wavelengths?

• Optical lithography is defined as a lithographic technology that:
  – Uses photons to induce chemical reactions in a photoresist.
  – Has the potential for image reduction using projection optics.
  – Involves a transmission photomask.
Why are we running out of wavelengths?

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  – Uses photons to induce chemical reactions in a photoresist.
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No solution is apparent for wavelengths < 157 nm.
What goes wrong at $\lambda < 157$ nm?

- Photomasks today are made from fused silica.
- Fused silica has a number of advantageous properties.
  - Chemical stability.
  - Transparency for ultraviolet light.
  - No intrinsic birefringence.
  - A low coefficient of thermal expansion.
What goes wrong at $\lambda < 157$ nm?

- A low coefficient of thermal expansion.
  - 0.5 ppm/°C.
    - If a mask changes temperature by 0.1°C, then the distance between two features separated by 50 mm will change by 2.5 nm.
    - This change in registration can be absorbed into overlay budgets.
  - After reduction by 4×.

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2010</th>
<th>2013</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM $\frac{1}{2}$ Pitch (nm) = node</td>
<td>45</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Overlay</td>
<td>18</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>
What goes wrong at $\lambda < 157$ nm?

• The transparency of fused silica must be modified by fluorine doping to have adequate transparency for use as substrates for photomasks at 157 nm.
  – The transmission falls off sharply for smaller wavelengths.

• An alternative material must be used.
  – CaF$_2$.

• The coefficient of thermal expansion of CaF$_2$ is 19 ppm/$^\circ$C.
  – Versus 0.5 ppm/$^\circ$C for fused silica.

• The 2.5 nm of mask registration error becomes nearly 50 nm.
What goes wrong at $\lambda < 157$ nm?

There will be no optical lithography for wavelengths $< 157$ nm.

(Maybe. More later.)
What are our choices?

• We will need to operate very close to the resolution limit of the optics.

or

• We need to adopt a radically new approach to lithography.

• Either of these will be hard to do.
I will talk about three of the most difficult challenges going forward in lithography:

– Gate CD control.
– The introduction of completely new lithographic technologies.
  • Extreme Ultraviolet (EUV) lithography, for example.
– The escalating costs of lithography.
What will be the hardest problems?

• As one looks at the ITRS today, the biggest lithography challenges involve critical dimension (CD) control.
  – Particularly for microprocessors.

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
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</thead>
<tbody>
<tr>
<td>MPU/ASIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate length (nm, in resist)</td>
<td>75</td>
<td>65</td>
<td>53</td>
<td>45</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Gate length (nm, post-etch) (physical length)</td>
<td>53</td>
<td>45</td>
<td>37</td>
<td>32</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>Gate CD control (nm, 3 sigma, post-etch, 10% of CD, litho only)</td>
<td>4.3</td>
<td>3.7</td>
<td>3.0</td>
<td>2.6</td>
<td>2.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>
What will be the hardest problems?

Year

Final gate dimension (nm)

95 97 99 01 03 05 07 09 11 13

1994

2001

9 year acceleration!
What will be the hardest problems?

• CD variation results from a number of factors.
  – Reticles.
  – Exposure tools.
    • Stepper lenses.
    • Focus variation.
    • Dose control.
  – Resist processing.
    • Bakes, for example.
  – Line-edge roughness (LER).
  – Metrology.
What will be the hardest problems?
What will be the hardest problems?

- Suppose metrology accuracy needs to be 10% of requirements.

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2002</th>
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<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
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<tbody>
<tr>
<td>115 nm</td>
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<td></td>
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<tr>
<td>Gate length (nm, post-etch) (physical length)</td>
<td>53</td>
<td>45</td>
<td>37</td>
<td>32</td>
<td>28</td>
<td>25</td>
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<tr>
<td>100 nm</td>
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<tr>
<td>Gate CD control (nm, 3 sigma, post-etch, 10% of CD, litho only)</td>
<td>4.3</td>
<td>3.7</td>
<td>3.0</td>
<td>2.6</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>90 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metrology accuracy (nm, 3 sigma)</td>
<td>0.43</td>
<td>0.37</td>
<td>0.30</td>
<td>0.26</td>
<td>0.23</td>
<td>0.20</td>
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<tr>
<td>80 nm</td>
<td></td>
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<tr>
<td>70 nm</td>
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<tr>
<td>65 nm</td>
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</tr>
</tbody>
</table>

- Improvement will require attention to contributions that are a fraction of the total requirement.
  - Metrology will need to be capable of dealing with individual contributions.
What will be the hardest problems?

• Fortunately, we do not always need to measure resist features or CDs directly on the wafer to prove to ourselves that things have been improved.
  – Reticles can be measured at 4×.
  – Hotplates temperatures can be measured.
  – Lens aberrations can be measured by interferometry.

• It will still be hard!
Resolution

resolution = k_1 \frac{\lambda}{NA}
What will be the hardest problems?

- As we make features smaller, everything must be controlled better.
  - This becomes increasingly difficult the smaller $k_1$ becomes.
- We are reaching practical limits.
- We are also reaching *physical* limits.
How far can optical lithography go?

\[ \text{resolution} = k_1 \frac{\lambda}{\text{NA}} \]

\[ \geq 0.25 \]

\[ \geq 157 \text{ nm} \]

?
Resolution

\[ \text{resolution} = k_1 \frac{\lambda}{\text{NA}} \]

where:
- \( k_1 \) is a constant
- \( \lambda \) is the wavelength
- \( \text{NA} \) is the numerical aperture

\[ \text{NA} = n \sin \theta \]

Lord Rayleigh (John Strutt)

Ernst Abbe
Immersion lithography

• One way to increase the numerical aperture is to employ immersion imaging.

• Immersion can potentially enable NA > 1.
  – This technology will have its own challenges.
Immersion lithography

- Immersion lithography challenges:
  - Moving wafers in and out of the fluid.
  - Scanning.
  - Bubbles.
  - Immersion fluid transparency at 157 nm.
- Work on this has begun only recently.
  - Time and money are needed for proof-of-principle and development.
What is the resolution limit of immersion lithography?

\[
\text{resolution} = k_1 \frac{\lambda}{\text{NA}}
\]

- Assume
  - \( k_1 > 0.25 \) theoretically, but \( k_1 \geq 0.3 \) is more realistic.
  - \( \lambda = 157 \text{ nm} \)
  - \( \text{NA} = 1.3 \)
  - Resolution of optical immersion lithography > 36 nm.
Next Generation Lithography

To overcome the limits of optical lithography, a different approach to lithography will be required.

- EUV lithography.
- Electron projection lithography (EPL).
- Maskless lithography

Any one of these will require significant advances in exposure tools, resists, masks (except maskless) and metrology.

We have invested 25 years in learning about projection optics, optical resists, and optical masks.

With a change in technology type, we need to start over.
EUV Lithography

- EUV lithography involves reflection optics and masks.

\[ \text{NA} = 0.14 \]
\[ \lambda = 13.4 \text{ nm} \]
EUV Lithography

- High reflectivity is achieved through the use of multi-layer Bragg reflectors.
EUV Lithography

- Multilayers will need to have well controlled peak wavelengths.

New metrology capabilities will be required.
EUV Lithography

- Mask flatness is required well beyond anything required currently.

Spec for flatness = 45 nm P-V at the 32 nm node.
For EUV ($\lambda = 13.4$ nm), $33$ Å = $180^\circ$ out of phase

How do we detect this?

Absorber

Multilayer reflector
EUV Lithography

- Examples of new metrology capabilities required for EUV lithography.
  - Flatness measurements for masks.
    - 10’s of nanometers of accuracy.
  - Reflectance at EUV wavelengths.
  - Mask defect detection.
    - < 50 nm in width and only a few nm high.
  - Surface roughness < 1 nm (rms).
The next big step lithography

- There are a number of options for the next step in lithographic technology.
  - EUV Lithography.
  - Electron Projection Lithography.
  - Maskless lithography.

- All of these require major advances in technology.
  - Tools.
    - Light sources.
  - Resists.
  - Masks.
  - Process control.

- Major advances are hard to do.
Lithography costs

Historical tool prices

Year

Exposure tool price

$0

$10,000,000

$20,000,000

$30,000,000

$40,000,000

$50,000,000
Lithography costs

Exposure tool price over time from 1980 to 2005, showing historical tool prices.
Lithography costs

lower is better
Lithography costs

![Graph showing the trend of tool price per silicon area/hour over the years from 1980 to 2020. The x-axis represents the year, and the y-axis represents the price in arbitrary units. The graph shows a decreasing trend up to 2010, followed by an abrupt increase. The text "lower is better" is indicated on the graph.](image)
Lithography costs

• The problem may not be just which lithographic technology is cheaper.

• The problem may turn out to be:

   What lithographic technology will enable the semiconductor industry to continue to produce higher performance PCs for less than $1000?
How do we pay for the R&D?

- The semiconductor industry made money when there were three years between nodes.
- I have seen no economic analysis that says two years per node maximizes profits for our industry.
  - The worst downturn in the history of our industry has occurred with a two year/node pace.
  - I do not think that one year per node is the answer.
- Innovation is needed.
  - Slow down and think!
Summary

- The end of optical lithography is finally approaching.
  - But not immediately!

- Introducing new lithographic technologies will be hard and expensive.

- The speed at which the semiconductor industry travels over the roadmap will slow down.
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