eBeam Initiative Luncheon
SPIE – February 14, 2012

Aki Fujimura
CEO – D2S, Inc.
Managing Company Sponsor – eBeam Initiative
The eBeam Initiative:

- Is an educational platform for all lithography approaches including Maskless and Imprint
- Open to any company in the semiconductor design chain with an interest in eBeam technologies
2010 Design for eBeam (DFeB) Roadmap: Complex Mask Shapes are Required at 20 nm & Beyond
2011 Design for eBeam (DFeB) Roadmap: Sub-80-nm Discontinuity Has Arrived

The old assumption: Dose Margin is independent of shape
The new world: Dose Margin depends on shape and size
2012 Design for eBeam (DFeB) Roadmap: Importance of Mask CD Uniformity

Roadmap Themes
- Mask write times
- Total cycle times
- Mask accuracy
- Wafer quality
- Design for eBeam Methodology

2010
- Complex masks
- Overlapping shots – circles, VSB
- Model-based mask data prep (MB-MDP)

2011
- Thermal analysis of overlapping shots
- Dose control for accuracy
- Double simulation for more accurate analysis of wafer quality

2012
- Mask CD Uniformity improvements
- Accurate measure of mask goodness
- Full chip MB-MDP

2013
- Design for eBeam (DFeB) mask methodology
- Incorporating eBeam Initiative technology roadmap
Today’s Speakers

- **Insights into Mask CD Uniformity Improvement**
  - Ryan Pearman, Director of Modeling – D2S, Inc.

- **A Scaling Path to 10/11nm using Complementary e-Beam Lithography (CEBL)**
  - Mike Smayling, Sr. VP Product Technology – Tela Innovations, in collaboration with CEA-Leti

- **Q&A**
Improving CD Uniformity
eBeam Technologies to Improve Mask CDU

• Dose Modulation
• Mask Process Correction (MPC)
• Model Based - Mask Data Prep (MB-MDP)
  • Enables overlapping shots, dose modulation and circular (or any shape) shots
• Circular eBeam Shots
  • Requires MB-MDP and machine support
Writer Support of Circular Apertures

Graphics and pictures courtesy JEOL, Ltd.
Circles in Addition to Rectangles

Dose provided:

<table>
<thead>
<tr>
<th>Dose</th>
<th>16.0 uC/cm²</th>
<th>19.7 uC/cm²</th>
<th>24.3 uC/cm²</th>
</tr>
</thead>
</table>

Shot diameter = 118

Hole Diameter on mask (measured)

<table>
<thead>
<tr>
<th>Diameter (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89nm</td>
</tr>
<tr>
<td>106nm</td>
</tr>
<tr>
<td>115nm</td>
</tr>
</tbody>
</table>

Shot Diameter = 142

Hole Diameter on mask (measured)

<table>
<thead>
<tr>
<th>Diameter (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>132nm</td>
</tr>
<tr>
<td>141nm</td>
</tr>
<tr>
<td>150nm</td>
</tr>
</tbody>
</table>

Shot Diameter = 334

Hole Diameter on mask (measured)

<table>
<thead>
<tr>
<th>Diameter (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>319nm</td>
</tr>
<tr>
<td>328nm</td>
</tr>
<tr>
<td>336nm</td>
</tr>
</tbody>
</table>

Resist: FEP171 (300nm)

Graphics and pictures courtesy JEOL, Ltd.
Continuous Range of Diameters from Discrete Aperture Sizes by Dose Modulation

JEOL JBX-3200MV allows each shot to be assigned one of 4095 dose values

Graphics and pictures courtesy JEOL, Ltd.
Sample Pattern Written with Circles

Test Case Courtesy of Samsung Electronics

Graphics and pictures courtesy JEOL, Ltd.
Machines Support Circles

• To write continuously variable sizes of circles, two things are needed
  • Discrete sizes of circular apertures
  • Dose modulation per shot to shoot the in-between sizes

• Customer orders accepted for this capability at JEOL

• 2012 focus: CDU improvement
  • Substantial shot count savings and CDU improvement achievable
  • CD Split avoidance and Dose Margin improvement is expected in writing complex mask patterns
Insights into CD Uniformity Improvements

Ryan Pearman
Director of Modeling – D₂S, Inc.

Robert Pack
D₂S, Inc.

www.ebeam.org
Critical Dimension Uniformity (CDU) on Mask

Mask Accuracy

Nominal CD
- CD Linearity
- Mask Process Modeling

CDU
- Dose Margin
- CD Split
Dose Margin is a Key to CDU
Dose Margin is Best with Circles

90 nm x 45 nm VSB Shot

Simulated Image

Dose Margin

Bad DM (red -- left and right)

Great DM everywhere

72 nm Circles
CD Split is Another Key to CDU

Desired Mask Shape

One Shot Solution
No CD Split

Two Shot Solution
With CD Split

When two edges of a critical dimension are written with two different VSB shots, positional error of the writer translates to worse CDU.
“CD” is measured between two wavy line edges and is a proxy for “running average” of energy transmitted through the mask to the wafer.

Shots 5 and 6 splits the CD.
With circles, diameter draws the CD regardless of the angle.

The natural overlap also reduces the LWR of the feature – it is closer to the diagonal that was desired.
D₂S Simulation Experiment

- Monte Carlo simulation of effect of shot and dose variability on many long 30 degree lines
  - Vary dose ($\sigma=5\%$)
  - Vary position ($\sigma=1.5\text{nm}$)
- Objective: See the result in CD variation due to the combined dose and positional changes

**Ideal shots**

**Varied shots**
D₂S Simulation Experiment

Conventional VSB
- Lower tolerance for shot placement error (CD Split)

MB-MDP Rectangles

MB-MDP Circles
- High tolerance for shot placement error
- Potentially higher fidelity, CD Uniformity
- Potentially lower cost if shot width can be increased for same fidelity
MB-MDP Improves Mask CDU

>30% CDU improvement for overlapping shots with the same shot count

<table>
<thead>
<tr>
<th></th>
<th>&lt;CD&gt; Range</th>
<th>&lt;CD&gt; Sigma</th>
<th>&lt;LWR&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>2.66</td>
<td>0.49</td>
<td>4.13</td>
</tr>
<tr>
<td>MB-MDP Rectangle</td>
<td>1.95</td>
<td>0.33</td>
<td>2.83</td>
</tr>
<tr>
<td>MB-MDP Circle</td>
<td>1.72</td>
<td>0.32</td>
<td>2.70</td>
</tr>
</tbody>
</table>
MB-MDP with Circles
Reduces Shot Count and Improves Mask CDU

Conventional

MB-MDP with Circles

Shot count reduction

Conventional

MB-MDP with Circles

CD (nm)

σ = 0.49  0%

σ = 0.395  41%

σ = 0.381  37%

σ = 0.393  33%

σ = 0.389  16%

σ = 0.314  0%

20.0 S/μm

11.8 S/μm

12.5 S/μm

13.3 S/μm

16.7 S/μm

20.0 S/μm
eBeam Initiative Member Collaboration:
Complementary eBeam Lithography (CEBL)

- 1x writing of wafers
- No decorations or SRAFs
- >10 WPH required vs. hours/mask

- Great depth of focus
- Stitching accuracy more difficult
Complementary e-Beam Lithography
Sub-20nm Collaborative Results

Michael Smayling, Jérôme Belledent, Laurent Pain
Topics

- CMOS Technology Scaling Below 20nm
- Design and Lithography Solutions
- Optical Results
- Complementary e-Beam Lithography
- eBeam Initiative Project
# CMOS Technology Scaling

<table>
<thead>
<tr>
<th>Node:</th>
<th>22</th>
<th>20</th>
<th>16</th>
<th>14</th>
<th>11</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Pitch</td>
<td>90</td>
<td>82</td>
<td>64</td>
<td>58</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>Y-Pitch</td>
<td>70</td>
<td>62</td>
<td>50</td>
<td>44</td>
<td>36</td>
<td>32</td>
</tr>
<tr>
<td>Gate Cut (X – Y)</td>
<td>90 x 35</td>
<td>82 x 31</td>
<td>64 x 25</td>
<td>58 x 22</td>
<td>46 x 18</td>
<td>42 x 16</td>
</tr>
<tr>
<td>M1 Cut (X – Y)</td>
<td>45 x 70</td>
<td>41 x 62</td>
<td>32 x 50</td>
<td>29 x 44</td>
<td>23 x 36</td>
<td>21 x 32</td>
</tr>
</tbody>
</table>

- Gate lines are vertical, so they use the X-pitch.
- Metal-1 lines are horizontal, so they use the Y-pitch
- Cuts for critical layers of Gate and Metal-1 are listed

- These are estimates based on experience, not specific wafer fab information
Design and Lithography solutions

\[ \lambda/NA = 143\text{nm} \] is the limit of optical systems today.

Tela’s patented and patent pending 1D gridded design style allows splitting the circuit pattern into lines and cuts.

For pitches < 80nm, pitch division is needed for lines.

The cuts need single to multiple optical exposures or CEBL.
Optical Results to 16nm

- Tela’s patented and patent pending 1D gridded design style
- Canon + Sequoia simplified OPC
- TEL SDP and optical cut processing
- 8326-39 on Thursday morning will have more details

16nm Metal-1
Complementary e-Beam Lithography

1D Lines → Resist → CEBL Patterning → Etch & Strip

From design... 1D Layout in Design File → Line Pattern → 193i with Pitch Division → CEBL

...to silicon 1D Layout on Wafer
eBeam Initiative Project

- Following SPIE Advanced Lithography in 2011, there was an interest amongst several members to investigate the limits to CEBL with currently available equipment and processes
- The eBeam Initiative facilitator brought together several potential collaborators
- After several exploratory meetings, we converged on a project involving CEA-Leti and Tela Innovations
- In a truly collaborative spirit, with very open discussion and debate, we eventually planned and carried out the project to be presented today
- Please note that the CEA-Leti team really did the “heavy lifting” to make this a success!!
Our CEBL Results to 11nm Node

- Tela’s patented and patent pending 1D gridded design style
- Joint testchip
- CEA Leti data processing and wafer processing
- Exposure on Vistec system

- 8323-14 on Tuesday afternoon (right after our luncheon)
Summary

- CMOS scaling can continue with optical lithography alone through 16nm
- e-Beam will complement optical lithography below 16nm
- Tela’s patented and patent pending 1D design style supports the decomposition into lines and cuts needed for both optical lithography and CEBL
- This “proof point” shows the value of collaboration and is just the beginning of the path to production
Acknowledgements

• Special thanks to the CEA-Leti team:
  • Jérôme Belledent (here today) and Laurent Pain
  • J. Pradelles, P. Pimenta-Barros, S. Barnola, L. Mage, B. Icard, C. Lapeyre, S. Soulan
  • The wafer fab processing team

• Visit us on the web at
  • www-leti.cea.fr/en
  • www.tela-inc.com
Thank You to Members for Your Contributions

- Membership in the eBeam Initiative grows to 42
- eBeam technologies improve mask CDU
- Machines support circular eBeam shots for improved CDU
- eBeam maskless technology will complement optical lithography below16nm
- SPIE papers presented by eBeam Initiative members
  - Advantest, CEA-Leti, e-Shuttle, EQUIcon, Fujitsu, Fraunhofer-CNT, Multibeam, Synopsys, Tela Innovations, Vistec