eBeam Initiative Luncheon
PMJ – April 19, 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

20nm

28nm

14nm

Courtesy: IBM

Courtesy: Samsung

Courtesy: DNP
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
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
Today’s Speakers

• CD Uniformity Improvements using VSB Shots
  – Ryan Pearman, D2S, Inc.

• MB-MDP Impact on Mask Accuracy and Write Times
  – Yasuki Kimura, HOYA

• Proof Point on MB-MDP and Wafer Quality Simulation
  – Gek Soon Chua, GLOBALFOUNDRIES

• Q&A
CD Uniformity Improvements Using VSB Shots

Ryan Pearman
Director of Modeling – D2S, Inc.

Bob Pack

www.ebeam.org
Which mask do you want?

Mask CDU
100nm (4x) HP
30 degree angle

Write time 0.7 a.u.
sigma = 0.9nm

Write time 1 a.u.
sigma = 0.6nm

Write time 1 a.u.
sigma = 0.9nm

Write time 0.7 a.u.
sigma = 0.9nm
From a wafer fab perspective, improving CD accuracy is important. Reducing CD variability is key. What can the Mask Shop contribute to our customer's success?
Dose Margin is a Key to CDU
Dose Margin and VSB Shots

90 nm x 45 nm VSB Shot

Simulated Image

Dose Margin

Worse Dose Margin when printed features deviate from drawn

• Small features
• Line-ends
• Sharp corners
• Tight pitch

Conventional MPC cannot address problem
MB-MDP overlapping shots creates margin
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
Modulating CD split with overlap

100 line
30° angle
0 overlap

Edges out of phase
Minimum LWR
1.5 shots per CD

100 line
30° angle
25nm overlap

Edges in phase
Maximum LWR
1 shot per CD

100 line
30° angle
50nm overlap

Edges out of phase
Minimum LWR
1.5 shots per CD

100 line
30° angle
100nm overlap

Edges half phase
Medium LWR
2.5 shots per CD

Minimum LWR
Edges out of phase
1.5 shots per CD

Maximum LWR
Edges in phase
1 shot per CD

Medium LWR
Edges half phase
2.5 shots per CD
Modulating Dose Margin with Overlap

100 line
30° angle
0 overlap

1x dose
Low dose exterior corner
Low dose interior corner

100 line
30° angle
25nm overlap

1.2x dose
Low dose exterior corner
High dose interior corner

100 line
30° angle
50nm overlap

1.4x dose
High dose exterior corner
High dose interior corner

100 line
30° angle
100nm overlap

1.3x dose
High dose exterior corner
High dose interior corner
Overlapping VSB shots provide options

- In the past, we have not had to think about shot optimization. There was really only one way to do things.
  - Shape defines your shot placement
    - VSB restricted to manhattan (0,90,+/−45) angles
    - Arbitrary shapes at a cost of finer manhattanization
      - Costs in both write time and CDU.
  - Minimize overall number of shots (write time)
  - Co-optimize CD-split minimization with sliver avoidance (CDU)
    - Cost to write time for this

- Introduction of overlapped VSB shots provides an extra degree of freedom
  - Can it be possible to improve on all three elements at the same time?
    - Reduce or remove shape restrictions?
    - Simultaneously write a mask faster while improving overall CDU?
Simulation Experiment

- Monte Carlo simulation of effect of shot and dose variability on many long 30 degree ILT srafs
  - Vary dose (σ=5%)
  - Vary position (σ=1.5nm)
  - Vary shot density (50-100% of conventional shots)
    - Affects: aspect ratio of rectangles, degree of overlap
CDU at constant pitch

<table>
<thead>
<tr>
<th>shot count</th>
<th>width</th>
<th>average</th>
<th>sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>50</td>
<td>99.9</td>
<td>0.9</td>
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<tr>
<td>100</td>
<td>75</td>
<td>99.9</td>
<td>0.7</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>99.9</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>100.0</td>
<td>0.7</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>99.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Optimal amount of VSB overlap which minimizes overall CDU at a given shot density.
Determining the optimal shot

Optimal for write time

Optimal for Mask CDU

30% CDU improvement!

100nm (4x) HP

30 degree angle

Conventional
Which mask do you want?

Write a mask with 33% better wafer variability

OR

Write a mask in 70% of the time

OR

Anywhere in between

Overlapping VSB: Yield improvement

Time to market

Write time 1 a.u.
3.6nm, 6sigma

Write time 1 a.u.
5.4nm, 6sigma

Write time 0.7 a.u.
5.4nm, 6sigma

Mask CDU
100nm (4x) HP
30 degree angle
Model-Based Mask Data Preparation Impact on Mask Accuracy & Write Times

Mask Division
HOYA Corporation
19 April 2012
eBeam Initiative Lunch
Motivation

• **Fidelity Limit**

• **Too Much Writing Time for SMO mask.**
  14nm node needs 2X~8X shot counts than 22nm node
  @ previous eBeam Initiative Lunch Meeting

• **Limit of Rule Base Correction of SRAF.**
  CD of Main pattern is closing to CD of SRAF.
  we shall apply model base correction to main.
Limit of Fidelity

\[ \beta_{\text{eff}} = (\beta_{\text{beam}}^2 + \beta_{\text{Resist}}^2)^{1/2} \]

Beam Blur \( \beta_{\text{beam}} \) of 50kV VSB EB Writer is Constant for More than 10 years.

The progress of Resolution (\( \beta_{\text{eff}} \)) has been made.

More smaller \( \beta_{\text{beam}} \) is required.

HOYA does not agree too high current!

**Advanced Resist**

Beam Blur \( \beta_{\text{beam}} > \) Resist Blur \( \beta_{\text{Resist}} \)

Advancement of Resist decrease to enhance Resolution.

\( \beta_{\text{eff}} \): Effective Blur, \( \beta_{\text{beam}} \): Beam Blur, \( \beta_{\text{Resist}} \): Resist Blur
Why MB-MDP is Good for Mask Making

Requirements: Shot count reduction, Fidelity Enhancement, Works well with our machine

MB-MDP: Dose, Figure, Overlap + OAperture

To achieve challenging requirements, we need as many dimensions of correction flexibility as possible! MB-MDP has the most dimensional control.
**Experimental**

MB-MDP condition
\(\beta_{\text{eff}} = 25\text{nm}, \ Eth = 0.5\)
Single Gaussian

Test Pattern
Phase 1: Qualitative analysis
  - SMO
    3D: Dose, Figure, Overlap
Phase 2: Quantitative analysis
  - Diagonal
    2D: Figure, Overlap

**Error Analysis**

- Per Pixel Edge Error.
  - Compare EB-simulated image by shots with target image.

**Overlay Image**
- Overlay to check visibly.

**Pixel Edge Error**
Measure distances between edges per pixel and take statistics.
(Mean, Sigma, Max.)
SMO (Qualitative analysis)

- Target hp64 60nm Hole 6% HT
- No Limitations of MRC & DRC. Example for 8nm Gaps on mask

Original

Conventional

MB-MDP

10 Shots SMO 2266 Shots MB-MDP 267 Shots

1/8 Shot Count Reduction
Less than Conventional!

Per Pixel Edge Error (nm)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Sigma</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01</td>
<td>1.36</td>
<td>6.78</td>
</tr>
</tbody>
</table>
New type of DRC & MRC are necessary. More Model calibration is progressing to realize this pattern on Mask.

exposed with JBX-3200
Diagonal (Qualitative analysis)

- Isolated Line for each CD & angle combination
- CD 40~200nm
- Angle 0~165° step 15°
  Too much data, So we report only 135°.
- Line Length 20um
- 2D: Figure, Overlap Same shot rank in One Line.
- JBX-3200 exposed Diagonal.
- Basic Dose of Block changes.
- CD, LWR, Dose Margin
- MB-MDP Aims Dose Margin
MB-MDP Fracturing Policy

MGN Pattern
Pitch = Shot Width = Shot Height

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Rectangle with pitch $48\text{nm} \div 2 \times \beta_{\text{eff}}$</td>
</tr>
<tr>
<td>MGN1</td>
<td>Margin optimized width same pitch of Conventional</td>
</tr>
<tr>
<td>MGN2</td>
<td>Margin optimized with wider pitch (60nm) for 20% shot count reduction from Conventional.</td>
</tr>
</tbody>
</table>
## Comparison of MGN-Pattern SEM image

<table>
<thead>
<tr>
<th></th>
<th>Original 0</th>
<th>Conventional</th>
<th>MGN 1</th>
<th>MGN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td>-</td>
<td>Pit: 48</td>
<td>Pit: 48</td>
<td>Pit: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W: 282.8</td>
<td>W: 96</td>
<td>W: 120</td>
</tr>
<tr>
<td><strong>SEM Image</strong></td>
<td>200nm</td>
<td>200nm</td>
<td>200nm</td>
<td>200nm</td>
</tr>
<tr>
<td><strong>FFT</strong></td>
<td>No Peak</td>
<td>Pitch:67nm</td>
<td>Pitch:67nm</td>
<td>Pitch:83nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pitch:290nm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Measured CD: 200nm
- SEM images are appleid scan rotation
MGN1 has the Best LWR.

Measured CD is 200nm, Box : 2900nm, 256 Samples
MGN1 has better Dose Margin!
Now analyzing results more and will show them in detail at BACUS!

Measured CD is 200nm
Conclusion

- Model-based correction is required for Shot Count Reduction and Fidelity Enhancement.
- High Dimensional Correction is required to satisfy the increasingly difficult requirements.
- MB-MDP dramatically reduces shot count for complex patterns.
- HOYA found MGN1 has better Dose Margin! Now analyzing results more and will show them in detail at BACUS!
- More Model calibration is progressing.
Proof Point on MB-MDP & Wafer Quality Simulation

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Outline

- Motivation

- Results & discussion
  - Example 1: 20nm Non-ILT Metal LOGIC
    - Lithography simulation verification results
    - CD uniformity check (new during PMJ 2012)
  - Example 2: 20nm ILT Via SRAM
    - Quality & mask shot count reduction trade-off
    - Lithography simulation verification results

- Conclusions
Motivation

- Current solution is a step-by-step solution, OPC → Fracturing → VSB format with MPC, which constrains each other and eventually limit in maximizing Wafer PW.
  - MRC limits OPC flexibility
  - Mask Process (resolution limit, corner rounding) limits Free-Form OPC
  - Flat OPC signature requirement to mask limits Mask Process Optimization, such as mask resolution or CDU enhancement.

- It is ideal if we have a solution to optimize above interactive factors at the same time.
Example 1: Model-Based Mask Data Preparation (MB-MDP) for non-ILT metal

- Images show shot configuration and simulated mask contours for Main Features (left) and SRAFs (right).
- There are no abrupt mask contour differences for the main feature while maintaining close to 20% mask shot count reduction.
- While shot count for purely rectangular SRAFs cannot be further reduced, MB-MDP can correct the CD non-linearity observed at such small dimensions and get the SRAFs back to target.
- The simulated CD loss for those 60nm SRAFs is 5nm which gets corrected during the MB-MDP step.
Example 1: Description of test case preparation for non-ILT layout

Target

Conventional RET/OPC Rule-based SRAF

Baseline OPC data

Conventional OPC mask shape

MB-MDP mask shape
Example 1: Litho simulation verification on 20nm metal LOGIC

- MB-MDP improves shot count by 20%
- MB-MDP improves wafer CDU for some patterns by improving mask fidelity for small SRAFs
- PV Band, MEEF, and DOF are slightly improved with MB-MDP

**Wafer CD uniformity**

**Conventional OPC mask shape**

**MB-MDP mask shape**

**PV Band**

**MEEF**

**DOF**

“Green”: CDU improvement

“Yellow”: similar CDU

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Example 2: Description of test case preparation for ILT layout

- Target
- Ideal (free-form) ILT output
- Manhattandized with specified resolution and according to MRC rules
- Conventional fracturing of Manhattandized OPC shape
- ILT Manhattandized mask shape
- MB-MDP based on Ideal OPC shape (using overlapping shots)
- MB-MDP mask shape
Example 2: Litho simulation verification on 20nm Via SRAM

PV Band

MEEF

Worst PV band is 2.15x

Worst PV band is 1.75x

Worst MEEF is 1.53x

Worst MEEF is 1.48x

DOF

Via area wrt target

Worst DOF count is 440

Worst DOF count is 22

MB-MDP:

1. 33% shot count reduction
2. 30% better PV Band
3. 10% better MEEF
4. 50% better DOF
5. 30% better MTT
6. All improvements are shifting the whole curve (worst, best, and average all improve)

Shot count

1.0x

0.7x

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Example 2: 20-nm ideal ILT SRAM via patterns

**Conventional fracturing**
Manhattanizing resolution
- 25nm: 59%
- 15nm: 100%
- 5nm: 320%

**MB-MDP**
Shot count wrt MR = 15nm
- 25nm: 57%
- 15nm: 45%
- 5nm: 33%
Example 2: Wafer quality vs. mask shot count

- **Conventional Fracturing:** Manhattanized ILT required 13,000 shots and a 5nm resolution to get within 10% in PV Band of “ideal”
- **MB-MDP:** Using overlapping shots, the worst-case PV Band improved to the level of the “ideal” OPC for <3000 shots
- Litho performance similar to “ideal” shapes can be achieved by writing curvilinear shapes with MB-MDP
- MB-MDP improves the trade-off curve of litho performance vs. mask write times:
  - “Ideal” shapes are production worthy with this approach
Conclusion

- **Overlapping shots created by MB-MDP enable lowered shot count** (and therefore faster write times) while simultaneously maintaining or improving lithography process window on the wafer.

- **MB-MDP simulates the effects of shots to produce the OPC-desired contour on the mask plane.** This is effective to reduce shot count for complex masks generated by technologies like Source-Mask Optimization (SMO)/ Full Chip Mask Optimization (FCMO), or Inverse Lithography Technology (ILT).

- **The effectiveness of MB-MDP is verified on 20nm Non-ILT Metal LOGIC.** As main features & SRAF are corrected by MB-MDP, 20% shot count savings and wafer CDU improvement are achievable.

- **The effectiveness of MB-MDP is verified on 20nm ILT Via SRAM.** The result shows that MB-MDP can reduce variation in a 20nm SRAM contact level layout based on “ideal” inverse lithography patterns. The DOF, CDU, PV-band and MEEF are all dramatically improved while at the same time reducing the shot count by 33%.
Thank you

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