Curvilinear MPC in Zero Time

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After Inverse Lithography Technology (ILT) introduction, LSI design is no longer simple. The 2nd Innovation.

Written by VSB

Write time gets too long again!

Written by Multi-beam (262K beams)

Mask writer has already migrated from shots to pixels.
# Advantages of Multi-beam Mask Writer

<table>
<thead>
<tr>
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<th>Single VSB</th>
<th>Multi-beam</th>
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<tbody>
<tr>
<td><strong>Throughput</strong></td>
<td>As patterns get more complex, shot count increases and <strong>write time goes up exponentially</strong>.</td>
<td><strong>Write time should stay constant</strong> for complex patterns.</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>To reduce write time, it is necessary to increase the current density and keep the pass count as few as possible, which <strong>degrades stitching accuracy and resist heating effect</strong>.</td>
<td><strong>Same electron current is maintained by low current density by the massive # of beams</strong> to keep up with the low sensitivity resist, with <strong>less concern for resist heating effect</strong></td>
</tr>
<tr>
<td><strong>Dose control</strong></td>
<td>Exposure dose has to be controlled shot-by-shot only. If finer control is necessary, one must reduce the shot size and the throughput will be aggravated.</td>
<td>Exposure dose can be <strong>finely controlled at 16nm beam level</strong>, which opens the door for the writer to do <strong>inline mask process correction (MPC)</strong></td>
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</tbody>
</table>
Conventional Datapath

LSI design
  ↓
  polygon
  ↓
OPC/ILT
  ↓
  polygon
  ↓
MPC
  ↓
  polygon
  ↓
Fracture

MBF1.1
  ↓
Input
  ↓
MBF1.1
  ↓
rasterize
  ↓
bitmap
  ↓
Writing

MPC …
Mask
Process Correction

MBM-2000

2022/9/27
New MPC Flow with Curves (Solution.1)

MBF2.0 is the new data format of MBM-2000 which enables B-spline expression of curvy shape boundary.

- File size is kept compact if OPC/ILT outputs Bezier/B-spline curves directly, or
- Curve fitting is performed directly after OPC/ILT
- MPC handles Bezier/B-spline figures

New curve data format is being prepared by Intel, Samsung, TSMC, ASML, Siemens, Synopsys, D2S, etc.
MPC is moved to writer’s inline software and is handled in pixel domain rather than in geometry domain

This flow is what NuFlare calls “PLDC”, meaning “Pixel Level Dose Correction”
## Advantages of Inline Pixel-based MPC (=PLDC)

<table>
<thead>
<tr>
<th></th>
<th>Offline/Pipeline Figure-based MPC</th>
<th>Inline Pixel-based MPC (PLDC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Turn-around-time (TAT)</strong></td>
<td>As patterns get more complex, figure count increases and <strong>MPC time goes up exponentially</strong>.</td>
<td>MPC can be processed in the background of writing and the pixel count is constant. <strong>There is no additional TAT</strong>.</td>
</tr>
<tr>
<td><strong>Convergence</strong></td>
<td>Offline MPC has <strong>more degree of freedom</strong> in size and dose control. This is good in terms of having more combinations of solutions but it often requires more iterations and longer calculation time to find the best one.</td>
<td>Since the beam size is fixed, the dose solution can be obtained through less iterations to keep the calculation time within the machine writing time.</td>
</tr>
<tr>
<td><strong>Dose control</strong></td>
<td><strong>Exposure dose has to be controlled by figures</strong>. Finest control needs comparable figure size as writer’s beam size and figure count increase will be aggravated.</td>
<td>Because inline MPC knows the exact beam grid, it can <strong>give precise dose to the pixels</strong>.</td>
</tr>
</tbody>
</table>
PLDC works in Pixel domain instead of Geometry domain

- Benefit of PLDC
  - Fine dose control by 16nm pixels
  - Improved process margin and pattern fidelity by edge enhancement
  - No additional Turn-around-Time for MPC
Curvilinear Pattern printed by PLDC

From eBeam Initiative panel in BACUS 2017  Low sensitivity resist (~150 uC/cm²)

Mask Design  No PLDC  PLDC

Improved corner rounding can be confirmed visually

80 nm (wafer) contact

No PLDC  PLDC overlay
## Dose Latitude

**Dose Latitude (CD-Dose sensitivity) @ 25% density**

<table>
<thead>
<tr>
<th>No PLDC [nm/%dose]</th>
<th>w/ PLDC [nm/%dose]</th>
<th>Improvement by PLDC</th>
</tr>
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<tbody>
<tr>
<td>0.48</td>
<td>0.36</td>
<td>25%</td>
</tr>
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</table>

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Dose latitude is improved by PLDC
PLDC keeps EPE of C-pattern at around 3~4nm in 3σ

- Equivalent to Line Edge Roughness (LER)

H. Matsumoto et al., SPIE Vol. 11324-20 (2020)
Information Transfer Ratio: Theory

Contour results by SEM function (solid) vs. input sine curve (dashed)

\[ f(x) = A \sin \frac{2\pi x}{\lambda} \]

\[ g(x) = \frac{1}{\sqrt{\sigma_{\text{edge}}} \pi} e^{-\frac{x^2}{\sigma_{\text{edge}}^2}} \]

\[ \text{information transfer ratio} = e^{-\frac{(\sigma_{\text{edge}} \pi)^2}{\lambda^2}} \cdot A \sin \frac{2\pi x}{\lambda} \]

\( \lambda \) is a function of period \( \lambda \)

Input sine curve

Blur function

Patterned amplitude = information transfer ratio

Design amplitude

Periods: 80 nm, 120 nm, 160 nm, 200 nm

Ideal sin
Information Transfer Ratio: Results

Patterning Blur $\sigma_{edge} = \sqrt{\sigma_{gray}^2 + \sigma_{beam}^2 + \sigma_{process}^2 - \sigma_{PLDC}^2}$

- PLDC clearly improves information transfer ratio, i.e. patterning blur

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High dose resist + PLDC
High dose resist (~130uC/cm^2)
Low dose resist (~30uC/cm^2)
Conclusion

- Multi-beam writer had allowed customer to get away from the problem of shot count increase.
- It is regrettable if customer has to face the problem of figure count increase in MPC, again.
- But PLDC can set you free from figure count increase by moving MPC to inline datapath, because total pixel count is constant.
- Let us help redefining MPC flow to optimize the balance between figure domain’s work and pixel domain’s work, and get away from the figure count increase together.