Curvilinear masks: an overview
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Why Bother with Curvilinear Masks?

Don’t we have enough to deal with already?
Curvy is Better

Curvilinear ILT vs. Standard OPC: *First to fail site*

~85% increase in DoF

Source: Micron, ILT Curvilinear Mask Designs for Advanced Memory (ebeam.org)
85% say EUV masks with Some Curvilinear Shapes by 2023
According to 2020 Luminaries Survey Predictions

Manufacturing of curvilinear masks is enabled by multi-beam mask writers. How extensively will curvilinear shapes be used for leading-edge (EUV, 193i) masks intended for high volume manufacturing (HVM) by 2023?

- **193i Masks** (n=68)
  - Entire reticles of curvilinear shapes: 62%
  - A hybrid of mostly curvilinear shapes and some Manhattan shapes: 12%
  - A hybrid of mostly Manhattan shapes with some curvilinear shapes: 20%
  - Only Manhattan shapes including 45 degree shapes: 6%

- **EUV Masks** (n=61)
  - Entire reticles of curvilinear shapes: 62%
  - A hybrid of mostly curvilinear shapes and some Manhattan shapes: 33%
  - A hybrid of mostly Manhattan shapes with some curvilinear shapes: 15%
  - Only Manhattan shapes including 45 degree shapes: 6%
EUV Remains Top Reason to Buy Multi-Beam Writers
EUV precision ranked #1 reason in 2021 Luminaries Survey

Please rank the primary reasons for purchasing multi-beam mask writers. Note in the answers below, precision refers to CD uniformity as well as placement accuracy. n=81

#1: More precision required for EUV masks
#2: More throughput for EUV masks
#3: Curvilinear ILT for EUV masks
#4: Curvilinear ILT for 193i masks
#5: More precision required for 193i masks
#6: More throughput for 193i masks

N/A=6%  N/A=1%  N/A=9%  N/A=9%  N/A=10%  N/A=10%

Note: 1-6 on X-axis indicate # of respondents that ranked that question as that ordinal number with 1 = highest.
VSB can be Used for 193i Curvy Mask Shapes

For EUV, only Multi-Beam is Practical

(a) VSB shot count

Source: TrueMask® ILT MWCO: full-chip curvilinear ILT in a day and full mask multi-beam and VSB writing in 12 hrs for 193i, Pang, et al., Proc. SPIE 11327, Optical Microlithography XXXIII, 113270K (31 March 2020); https://doi.org/10.1117/12.2554867

(b) VSB shot configurations for 3 contact arrays; note POR OPC shot configurations not shown

MWCO : Mask-Wafer Co-Optimization
Pixel Manipulation Enables Curvy Masks

Multi-beam Mask Writer + Curvy ILT + GPU Acceleration = Curvy Masks
The Mask Ecosystem is Ready for Curvy ILT

Mask Data Preparation
- MDP
- MPC
- Mask Verification

Mask Writing
- VSB
- Multi-beam

Mask Metrology
- CD SEM
- Wafer Plane Analysis

Mask Inspection
- MPI
- WPI

Mask Review
- AIMS

Mask Repair
- eBeam
- Atomic force
Mask Rule Checking (MRC) for Curvy is Simpler

Large Curvatures are More Reliably Manufacturable

Pearman, et al, PMJ 2019
Curvy Masks Bias More Faithfully

10nm bias on curvy mask produces 10nm change on simulated mask

[1] $\Delta M$: edge displacement on the mask in nm
[2] $\Delta W$: edge displacement on the wafer in nm

[Design]
Rectilinear

[1.4x nm]

Bias (x)

Curvilinear

[~1.4x’ nm]

$\Delta W$ (x’’)

[10nm bias on curvy mask produces 10nm change on simulated mask]

[193i sim]

“MEEF”: 2.3

“MEEF”: 1.9

$\Delta W$ vs. Design Bias

[Graph showing bias (1x, nm) vs. $\Delta W$ (1x, nm)]

Curvilinear

Rectilinear

$\Delta W$ ratio (Curvi vs Recti)

D2S PATENTED TECHNOLOGY
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Mask Bias Translates Better to Wafer with Curvy
Curvy is 10% More Faithful to Mask Bias in ΔArea

- Design
- eBeam sim
- 193i sim

- Rectilinear ILT
- TrueMask® ILT

1.4x nm bias

~1.4x’ nm

~1.1x’’ nm

193i Simulation (ΔArea)

ΔArea on Mask vs. Design Bias

ΔArea on Wafer vs. Design Bias

- Curvilinear
- Rectilinear
- ΔArea ratio

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Curvy Masks are More Reliably Manufacturable

曲線型マスクはより信頼性の高い製造が可能

曲線型マスクのパターンニングがEUVプロセスウィンドウを拡大: 乱数シミュレーションを用いた検討

Ryan Pearman, et al, "How curvilinear mask patterning will enhance the EUV process window: a study using rigorous wafer+mask dual simulation", PMJ 2019
Curvy Masks Enable Curvy Designs

Curvy Designs are More Reliably Manufacturable, too

Curvy Designs:
• Better Yield
• Less power
• Faster
• Smaller

Source: Micron presentation at eBeam Initiative lunch SPIE-AL 2020

Source: imec poster at Photomask Technology 2019
Curvy Design?

Semiconductor Design Today

Old

New

Semiconductor Design Tomorrow

Minecraft, Mojang (Microsoft)

Death Stranding, Kojima Productions