O(\(p\)): GPUs, Pixels, DL, Curvy Masks & Designs
D2S Does GPU Acceleration

Curvy Shapes

Deep Learning

Pixel Domain

GPU Acceleration
GPU Accelerates Edge Manipulation, Too

Manhattan OPC

MB-MDP (overlapping)

VSB

Curvy ILT

MWCO*

Piecewise Linear Polygons

Curves (Bezier/Spline)

Pixels

Multi-beam

Fracturing

*MWCO: Mask-Wafer Co-Optimization
GPU is Great for Curvy

\[ O(p) \]

Because GPU is even better at pixels
GPU is SIMD and SIMD is Great at Pixels

Multiple Single Instruction Single Data (SISD)

Single Instruction Multiple Data (SIMD)
Mask and Wafer Effects are SIMD

Because nature is SIMD
Image Processing is SIMD, Too

Because Images are Arrays of Pixels

Source: NuFlare/CDLe

Source: Lasertec/BACUS Newsletter

Source: L Pang, et al., "Expanding the applications of computational lithography and inspection (CLI) in mask inspection, metrology, review, and repair"
Pixel-Based and Edge-Based are Duals

- Whatever you can do in one can be done in the other...given a resolution limit determined by “Nyquist”
- The only question is performance....

Multi-Beam Mask Writer

- Rasterization
  - 0%
  - 0%
  - 29%
- Contouring
  - 0%
  - 38%
  - 99%
  - 7%
  - 98%
  - 100%
This Also Rasterizes Exactly the Same

- Rasterization is inherently a low-pass filter
- Red and blue become the same in pixels, but red uses much more data
- Curvilinear format would also become the same in pixels and thereafter
  • And represents the actual contoured shape that would be on the physical mask
Mask-Making is Already Pixel-Based

Fracturing

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Pixels

Multi-beam $O(p)$

Inspection $O(p)$

Metrology $O(p)$

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Datapath is Not Multi-beam VSB

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Curvy ILT $O(p)$

Piecewise Linear Polygons

Curves (Bezier/Spline)

Pixels

$O(v) \sim O(v^{1.4})$

$O(v) \sim O(v^{1.4})$

Inspection $O(p)$

Metrology $O(p)$

*MWCO : Mask-Wafer Co-Optimization
D2S is Adding a Pixel-Based Datapath

Manhattan OPC

MB-MDP (overlapping)

VSB

Curvy ILT $O(p)$

Pixel $O(p)$

Multi-beam $O(p)$

Detection $O(p)$

Metrology $O(p)$

MWCO* $O(v) \sim O(v^{1.4})$

*MWCO : Mask-Wafer Co-Optimization
Edge or Pixel, Curvy Improves Manufacturing

*Simple example: Biasing*

For traditional Manhattan edge-based CAD, it is bad to have bias create curvy shapes. So this is understandable but incorrect. Etching, for example, doesn’t work that way.
Even a Simple Bias Operation is Better with Curvy

*Rectilinear bias is off by 40% on corners*
Even Worse is Manufacturing Variation

*Dose margin is bad on 90° corners*
Manufacturable Shapes are More Reliably Manufacturable

- Manhattan
  - Ideal mask: 4.6nm
  - Monte-Carlo Mask: 1.6nm
  - 20-50% reduction
- Curvilinear
  - Ideal mask: 1.9nm
  - Monte-Carlo Mask: 1.2nm
  - 30-50% reduction
- VSB
- Multi-beam

Manufacturable Shapes are More Reliably Manufacturable

*On Wafer, too*

First thing ILT does is to compute manufacturable curvy targets anyway.
I Presented This at Design Automation Conference

“I was in EDA physical design since 1979 so I know it’s important for you to know: Curvilinear Designs are Now Manufacturable. In fact, More Reliably Manufacturable.”
Is it Time to Break the Manhattan Assumption?

Most chips are interconnect-limited; Reducing vias will reduce routing congestion
Curvy Designs are Better for Designers, Too

- Manufacturable Curvy Designs
- Improves, all at the same time
  - Yield
  - Power
  - Performance
  - Area

- The barriers are:
  - VSB mask writing
  - EDA infrastructure
General Perception: “Everything has to Change”
Actually: Only Routing plus Performance Improvements
Curvy-Pixel-GPU Can Work for Them, Too

- Curvy Shapes
- Deep Learning
- Pixel Domain
- GPU Acceleration
Today’s GPU Workstation = 8,000 Cray-2s
60,000,000x Price Performance
It’s time to rethink EDA

Cray-2 (1985)
1.9 GFLOPS w/500MB @ $15M

nVIDIA RTX 3090 Ti (2021)
15,300 GFLOPS w/24GB @ $2,000
Today’s GPU Workstation = 8,000 Cray-2s

150,000,000x? 60,000,000x Price Performance

It’s definitely time to rethink EDA

Cray-2 (1985)
1.9 GFLOPS w/500MB @ $15M

Announced Last Tuesday

GEFORCE RTX 4090
24GB G6X
2-4X Faster than 3090 Ti
$1,599
Available October 12th