The lifetime of a mask is anticipated to be ~ 50,000 – 100,000 imprints.

An e-beam written master mask will cost ~ $500K.

If you wanted to print 1M wafers, you would spend ~ $500M on masks.

Go share that strategy with a fab manager!!!

The solution: create a Master Template that can easily be replicated.

Master ➔ Daughter approach.

Good news! You can use an imprinter to make the Daughter Templates.
Do Mask Replication Tools Exist?

Canon is also supplying mask replication tools to the industry

FPA-1100 NR2
Mask Replication Tool

<table>
<thead>
<tr>
<th>Target specifications</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>shots/hour</td>
<td>4</td>
</tr>
<tr>
<td>CD Uniformity</td>
<td>nm</td>
<td>0.8</td>
</tr>
<tr>
<td>Image Placement Accuracy</td>
<td>nm</td>
<td>1.0</td>
</tr>
<tr>
<td>Particle</td>
<td>pcs/replica</td>
<td>0.002</td>
</tr>
</tbody>
</table>

NR2 shipped in early 2017
Replication Example: Semiconductor

a) Master Imprint

b) Replica Mask

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Replication and Image Placement

- During replication, all the usual parameters need to be controlled, in addition to just feature resolution
  - Defectivity
  - Critical dimension uniformity
  - Image placement

- The data below indicates that final image placement can be as low as 2.5nm

<table>
<thead>
<tr>
<th>Master/Replica @2x nm</th>
<th>Target</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defectivity (pcs/cm²)</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>CD Uniformity (3σ, nm)</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Image Placement (nm, 3s)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>
What’s Left?

- I can write the mask
- I can etch the mask
- I can replicate the mask
- And I’ve satisfied requirements for CDU, IP and defectivity
- I’m done, right???

- NO!! Masks must be perfect. No defects can exist in a critical area of the mask. As a result, the mask must be inspected
- Inspected
- Repaired

*Imprint lithography is challenged by the fact that it is a 1x technology. This makes inspection and repair more difficult*
Inspection Methods

- **Optical Inspection - Mask**
  - KLA-Tencor: 6xx
  - Reflection/Transmission Mode

- **Electron Beam Inspection - Wafer**
  - Die-to-Die
    - KLA-Tencor eS35
    - HMI eScan315
  - Die-to-Database
    - NGR2100

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM ½ pitch (nm) (contacted)</td>
<td>59</td>
<td>52</td>
<td>45</td>
<td>40</td>
<td>36</td>
<td>32</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>Flash ½ pitch (nm) (un-contacted poly)</td>
<td>45</td>
<td>40</td>
<td>36</td>
<td>32</td>
<td>28</td>
<td>23</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Defect size, patterned template (nm) [V]</td>
<td>35</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>
Claymore: 32nm Programmed defect layout

- All sections (32nm, 40nm, and 48nm) have the same corner marks and unit cell step distances
  - $X = 2\, \text{um}$, $Y = 3\, \text{um}$

- 32 nm 40nm and 48nm feature types are the same design with different dummy shrinks.
Defect locations

- Programmed defects sizes are arrayed every 7 unit cells horizontally.
- Programmed defect types are arrayed every other unit cell vertically.
- Three repeats of each set.
- Separation between PD sizes: 14μm.
- Vertical and horizontal features.
- Other features types have a similar array of defects.
- Line space features.
- Separation between PD types: 6μm.
Programmed Defects for 32nm Patterns

Programmed defects start at 4nm and increase in increments of 4nm up to 48nm.

M1

4x32nm → 32x32nm → 32x48nm

L/S

Contact

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Mask and Imprint Analysis

- **SEMs of the Mask were captured with a Holon EMU-270A SEM**
  - 1.5 nm resolution at 1.0 kV when applying aberration correction.
  - Low vacuum and charge control enable high quality imaging on fused silica masks.

- **Images of the imprints taken with a JEOL JSM-6340F field emission cold cathode SEM**
  - 1.2 nm resolution capability at 15 kV and 2.5 nm at 1 kV.
32 nm Half Pitch Lines
PD measured area evaluation process

DAFC – Defect Analysis for the Financially Challenged

1. Smoothing & Threshold segmentation
2. Image Shift by pitch
3. Image A - Image B
4. Count white pixels and convert to area 2349 nm²
Measured area compared to data size

Mid-line extension

Shrinking Pillar
Electron beam inspection systems

- **KLA-Tencor eS35**
  - Die-to-die
  - Image contrast inspection
  - Pixel size: 15, 20, 25nm
  - Landing energy 1750V
  - Data rate 50mpps

- **Hermes Microvision eScan 315**
  - Die-to-die
  - Image contrast inspection
  - Pixel size: 10, 15nm
  - Landing energy: 2000V
  - Data rate 100mpps

- **NGR 2100**
  - Die-to-database
  - Fast CD inspection
  - Pixel size: 3nm
  - Landing energy 2600V
  - Data rate 50mpps
Programmed defect pixel progression

Programmed Defects

- 48nm (6nm)
- 40nm (5nm)
- 32nm (4nm)

Setup errors

15nm Pixel
20nm Pixel
25nm Pixel
80% capture rate examples

- The sensitivity range is 10 to 18nm for an 80% capture rate

![Graph showing capture probability against measure PD area (nm^2)](image)

- 327 nm^2: ~10nm PD
- 578 nm^2: ~18nm PD
**eScan 315: e-beam wafer inspection**

Parameters:
- 100 MPPS
- 2000V
- 3nA

- **32nm HP**
- **Metal-1**
- **Pillar**
- **Lines**

**Symbols**:
- **15nm pixel**
- **10nm pixel**

**Line Widths**:
- 48, 44, 40, 36, 32, 28, 24, 20, 16, 12, 8, 4 nm

---

[Canon Nanotechnologies, Inc.](#)
Captured Programmed Defects: 10nm Pixel

Programmed defects: 8nm – 12nm

<table>
<thead>
<tr>
<th>Metal-1</th>
<th>Pillars</th>
<th>Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mousebite</td>
<td>H Mousebite</td>
<td>H Mousebite</td>
</tr>
<tr>
<td>Line Shortening</td>
<td>V Mousebite</td>
<td>V Mousebite</td>
</tr>
<tr>
<td>Mid Extension</td>
<td>H Extension</td>
<td>H Extension</td>
</tr>
<tr>
<td>Line Extension</td>
<td>V Extension</td>
<td>V Extension</td>
</tr>
</tbody>
</table>

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KLA-T 6xx Optical Inspection Results

- Because the background noise is low, it is possible to discern the defect without resolving the 32nm pattern.
- The KLA-T 6xx platform works in both Transmitted and Reflected light modes.
- Transmitted and Reflected Light capture different types of defects. Having both modes essential for capturing critical defects.
- In these examples, one defect in the 32nm half pitch pattern has signal in transmitted and one in reflected mode.
Modulation vs. Programmed defect size

- Modulation tracks well with the measured defect size in the mask
- Sensitivity is on the order of 32nm
- Thresholds can be optimized to increase sensitivity
Infrastructure: Template Repair

RaveLLC

Nanomachining system

Nawotec

E-beam Deposition/Etch

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Repair Examples

After repair on a RaveLLC 650nm system

Before repair

Quartz Line
Quartz defect

After repair on a RaveLLC 650nm system

300 nm defect
50 nm defect
50 nm trench

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Zeiss: MeRiT MG E-beam Mask Repair

Before Repair

After Repair

#1  #2  #3

#1  #2  #3
Repairs: After Imprint

40nm

Before Repair

After Repair

Imprint

32nm

#2

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So is this technology really going to work?
Emerging Market Applications

*J-FIL™* nanopatterning advantages can serve a variety of markets

- **Semiconductor ICs**
- **Hard Disk Drives**

J-FIL’s low cost, high resolution patterning enables increase memory capacity at lower cost per bit.

Drives resolution and cost of ownership for both CMOS and magnetic memory.

Emerging Applications

- **Displays**
  - Efficiency
  - Cost
  - Brightness
- **Solar**
  - Efficiency
- **Batteries**
  - Capacity
  - Faster Recharge
- **Nano-Bio**
  - Drug Delivery
  - Targeting
  - And Efficacy

J-FIL enables a broad range of other market opportunities with low cost, high resolution, and large substrate area patterning.

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Full Wafer/Disk Imprint Process

Imprio 1100 (Photonic Crystals)

Thin Template

150mm Diameter Patterned Media Template

Imprio HD7000 (Patterned Media)
Hard Drives

- Hard disk drives operate by storing bits of information on a disk coated with a magnetically influenced film
  - Magnetic media

- These things have been working for years. What’s the problem?
The problem: thermal stability, write-ability, and density

Magnetic Stability: \( \frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy} \times \text{volume}}{k_B \times \text{temperature}} = \frac{K_u V}{k_B T} \geq 70 \)

**PROBLEM:**
- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy Ku
- This increases the medium coercivity and makes the medium more difficult to write

**SOLUTIONS:**
- Work with higher anisotropy:
  - Capped and exchange spring media
  - Thermally assisted recording (TAR)
- **Work with larger ‘grains’: patterned media**
Why Imprint Lithography for Patterned Media?

- Let’s compare the Information storage roadmap against the well established ITRS Roadmap for integrated circuits

- The Storage Roadmap is much more aggressive than the ITRS Roadmap
- High volume optical tools will not be available in time
- The price of an EUV printing tool is prohibitive ($50-75M)
- Electron beam writers have the resolution, but not the throughput
- Imprint offers the best combination of cost, throughput and resolution

Graph:
- MPU
- DRAM
- Flash
- Storage

- 193nm Next Generation Lithography
- 193i – no resolution
- EUV $$$, timing for 1Tb
- EBDW – Low throughput
- UV-IL – right combination

1Tb/in²

Year

Half Pitch
100 70 40 20 10 5 1

$90-100M
$100-150M
High Density Template Fabrication for PM

Conventional Method for defining small features

- Resist applied to <15 nm of Cr
- E-beam Exposure
- Etch chrome, strip resist
- Etch quartz, Strip chrome
- Fluorine based chemistry

Alternative methods include:
- PMMA or ZEP520A lift-off
- High Resolution HSQ resist
- Ion beam Lithography
Fabrication of Master Templates for Patterned Media requires high resolution patterning over large areas
- Sub-50 nm resolution
- Very low pattern distortion

Patterns are concentric lines, arcs, and dot arrays
Example: BPM – 25nm Half Pitch

- E-beam write
- Quartz etch
- CR Lift-off
- Imprint
Master Template Fabrication for 1Tb and beyond

- For Bit Patterned Media (BPM), a 1Tb Master requires a half pitch of 12.5 – 13.5 nm!
- While it may be possible to resolve these feature types with a Gaussian beam pattern generator, there are several problems that you will need to overcome
  - Pattern placement of the individual bits and write errors
  - Write time! (7 days at a minimum)
- An alternative approach is to combine the best attributes of e-beam writing and self assembly
  - Directed Self Assembly
Diblock copolymer materials undergo phase separation to form morphologies with short-range order.

- The morphology and phase dimensions are controlled by the chemical composition.
- Processing is simple and cheap, but **no long-range order**.

**Diblock Copolymer Self-Assembly**

- Polymer molecule
- Uniform film
- Spheres
- Cylinders
- Lamellae
Examples: Short-range order

- From Joy Cheng, IBM Almaden

Polymer solution is spincoated on an unpatterned substrate and then annealed for several minutes.

Cylinders

- ~1 micron

Uniform feature size and pitch, but no long-range order.
(Likely okay for PV applications)

Lamellae

- ~1 micron

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Directed Self Assembly

- To achieve long range order, we can use the e-beam writer to “guide” the placement of the block copolymer

Pattern Rectification

Density Multiplication

![Pattern Images](c) ![Pattern Images](g)

Half pitch = 13.5nm


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Another DSA Example

- rotary stage e-beam lithography
- directed block copolymer self-assembly + line doubling (if needed)
- circumferential and radial lines created in separate steps
  - at least double the effort to create a master BPM template (compared to hcp)
  - track pitch and bit pitch independent, and flexible BAR
  - possible to integrate other advanced patterning techniques such as SADP
  - compatible with offset field for servo
  - compatible with zoning and screw

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Feb. 25, 2014
Template Inspection
Candela X-Beam™ Optical Surface Analyzer

Multi-channel inspection of optical properties
- Scattered light $\rightarrow$ dark field
- Reflected light $\rightarrow$ bright field, reflectometry
- Phase shift $\rightarrow$ thin film measurements

This work:
- Candela 6120: disk substrates
- Candela CS20: templates

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Identifying Defects on Templates and Disks

- There are 3 critical defects that need to be tracked: template, particle, non-fill
- How do we identify each defect type (defect classification)?
- How do we track defectivity?
  - From template to disk
  - From disk to disk
Defect Source Analysis

- Total inspected area: ~ 29 cm²
- Total defectivity: ~ 2.4 def/cm²
Liquid Crystal Display Panel Fabrication

- LCD displays are ubiquitous:

LCD Panel Components

- Polarizer
- Glass Substrate
- TFT
- Liquid Crystal
- ITO Film
- Orientation Film
- Color Filter
- Unpolarized White Light
Nanoscale Patterning Can Improve Many Critical Components in Displays

J-FIL™ can offer improved technologies at lower cost that impacts approximately 50% of liquid crystal display Bill of Materials (BoM).
LithoFlex 350™

SYSTEM CONFIGURATION

- Plate-to-Roll (P2R) or Roll-to-Plate (R2P)
- Template Substrates:
  - P2R ≤ 300mm glass or silicon wafer
  - R2P ≤ 350mm width web
- Automated or manual template loading
- Automatic protective film particle control
- UV cure (365nm) light source

PERFORMANCE

- Sub-50 nanometer feature resolution
- Throughput > 1 meter per minute
- Position accuracy of 600 microns (3σ)
  - Alignment Option Available
- Print width: 300mm maximum

TECHNOLOGY

- Jet and Flash™ imprint technology
- IntelliJet™ resist jetting dispensing system

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Plate to Roll (P2R) imprinting

P2R imprinting uses patterned rigid substrates:

- As an example, a 300mm wafer can be used as the working template

- Can be patterned several different ways:
  - Photolithography
  - Imprint Lithography
  - Electron beam Lithography
  - Photo or E-beam/DSA
J-FIL Results

350mm web with protective film

Protective film removed

Pattern close-up
Test Pattern SEM images

- Both micron size and nanoscale patterns can be imprinted within the same field

Micron scale pattern

450nm test pattern
Nanoscale imprinting

50nm half pitch grating
Wire Grid Polarizers

Two methods for fabricating Wire Grid Polarizers (WGPs):

Very low cost

Very High Performance

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Etched WGP Results

- Performance is driven by many factors
  - Defectivity
  - Pitch
  - Duty Cycle
  - Aspect Ratio
  - Al quality

Integrated Transmittance: ~44%
Extinction ratio at 550nm: ~50K
Final Thoughts

**X-ray Lithography**
1X proximity-based technology using a membrane-based mask

**Ion Beam Lithography**
1X and projection technology using a stencil-based mask

**SCALPEL**
Projection electron lithography using a thin membrane mask

1. I worked on all three mask technologies
2. From a manufacturing perspective, all three are now dead
3. All three died, in part, from a lack of mask infrastructure
Acknowledgments

CNT and Molecular Imprints
Ecron Thompson, Gerard Schmid, Mike Miller, Kosta Selinidis, Ian McMackin, Cindy Brooks, Gary Doyle, Gaddi Haase, Kang Luo, Lovejeet Singh, David Curran

DNP
Shiho Sasaki, Nobuhiro Toyama, Masaaki Kurihara, and Naoya Hayashi

Motorola
Bill Dauksher, Kevin Nordquist, Kathy Gehoski, Ngoc Le, Eric Ainley, Steve Smith

KLA-Tencor
Mark McCord

Vistec-Semiconductor
Tim Groves, Mike Butler, Eric Tapley, Olaf Fortagne

Photronics, Toppan Photomask, IMS Chips, NGR, LBNL, Rave LLC, Zeiss, NuFlare, Mentor Graphics, HMI

This work was partially funded by:
DARPA (N66001-02-C-8011, N66001-01-1-8964) and NIST-ATP

Canon Nanotechnologies, Inc.
References

- To learn more about Jet and Flash Imprint Lithography, go to:
  - [http://cnt.canon.com/technical-library/](http://cnt.canon.com/technical-library/)
Appendix

**Applications**
- Photonic Crystals
- Contacts
- Memory
- Dual Damascene
- Micro Lens Arrays
- SAW Devices
An Example: Photonic Crystal – 80nm HP

Example: Photonic Crystal Array – Pattern Transfer

After Planarization

After Imprint

After Dry Develop

After Cr/Glass etch
The Complete S-FIL Process: Contacts

- Template: 80 nm dense pillars
- Imprinted Etch Barrier
- Etched 80 nm contacts
Hoya: 30nm IBM Memory

Template

Imprint

Si Etch

X-Section

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Dual Damascene
Micro Lens Arrays

**Background:** Added to a digital camera’s CMOS/CCD image chip to improve optical collection efficiency

**Challenge:** Patterning of high packing density aspheric lens arrays requiring no etching

Template

Imprinted Lens Array

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SAW Device Fabrication

**Step 1. Create Template**

![Image of template](image1.png)

**Step 2. Imprint, etch the aluminum IDT, and remove the resist**

![Image of aluminum and substrate](image2.png)

The patterned aluminum (light grey) is 40 nm thick × 130 nm wide, and the substrate material (dark grey) is LiNbO$_3$.

Note the line uniformity and the absence of line edge roughness in the final pattern.