COHERENT EUV LITHOGRAPHY
WITH TABLE-TOP LASER

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PhD Final
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Outline

• Nanotechnology, applications, techniques
• Capillary Discharge Laser
• Holographic projection lithography
• Generalized Talbot Imaging lithography
• De-magnified Generalized Talbot Imaging lithography
• Defect Tolerance in the Generalized Talbot Imaging
• Summary
“There is plenty of room at the bottom”

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord’s Prayer on the head of a pin. But that’s nothing; that’s the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Richard P. Feynman, 1960
The Scale of Things – Nanometers and More

Things Natural

- Ant
  - ~5 mm
- Dust mite
  - ~200 μm
- Human hair
  - ~60-120 μm wide
- Red blood cells
  - ~7-8 μm
- ATP synthase
  - ~10 nm diameter
- DNA
  - ~2-1/2 nm diameter
- Atoms of silicon
  - Spacing 0.078 nm

Things Manmade

- Head of a pin
  - 1-2 mm
- MicroElectroMechanical (MEMS) devices
  - 10-100 μm wide
- Pollen grain
  - Red blood cells
- Zone plate x-ray “lens”
  - Outer ring spacing ~35 nm
- Self-assembled, Nature-inspired structure
  - Many 10s of nm
- Nanotube electrode
- Carbon buckyball
  - ~1 nm diameter
- Carbon nanotube
  - ~1.3 nm diameter

- 1,000,000 nanometers = 1 millimeter (mm)
- 1,000 nanometers = 1 micrometer (μm)
- 1 nanometer (nm)
- 0.1 nm
- 10 nm
- 100 nm
- 0.1 μm
- 10 μm
- 100 μm
- 0.1 mm
- 1 mm
- 10 mm
- 1 cm

The Challenge

Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.
Nanotechnology

“ability of engineering materials precisely at nanometer scale”

Norio Taniguchi, 1974
Applications

Techniques of nanofabrication

1. EUV lithography - 8nm
2. Electron beam lithography - 2.5nm
3. Scanning probe lithography - 6nm
4. Nano imprint lithography - 10nm
Parameters of the Capillary discharge laser @ 46.9 nm

- Spectral bandwidth: $\Delta \lambda / \lambda = 3.5 \times 10^{-5}$
- Power: miliwatts range
- Energy: typ. 0.1mJ-0.8mJ

Spatial coherence

Characterization of spatial coherence:
Young’s interferometer

Temporal coherence

$\Delta \lambda / \lambda \sim 3.5 \times 10^{-5}$

Nanoscale coherent lithography with table top EUV laser

Holographic projection lithography

GTI

DGTI
Diffractive mask design and fabrication for EUV wavelengths
EUV Diffractive Mask

Membrane (Silicon and Silicon Nitride)

Mask (Resist)

Frame (Silicon)

~25nm

~70nm

~200nm

13% Transmission

36% Transmission

1.7% Transmission

13% Transmission

Silicon Nitride
EUV Diffractive Mask – fabrication challenges
Mask Fabrication Protocol

1. Spin Coating HSQ
2. Spin Coating ESPACER
3. E-beam lithography
4. Developing
5. Rinsing

- NaOH/NaCl/H₂O
- H₂O
Mask Fabrication EBL

http://www.cnf.cornell.edu/image/spiefig1.jpg
Overpassing mechanical tolerances
Holographic projection lithography
Holographic projection lithography

CGH calculation steps
Hard threshold

Binary object

Fresnel propagation (cont. tone hologram)

Half-toning

Binary hologram

Reconstruction
Half-toning by hard threshold

Binary objects and corresponding binary CGHs

- $\lambda = 46.9\, \text{nm}$
- Pixel Size = $140\, \text{nm}$
- $Z = 500\, \mu\text{m}$
- Field = $102.9\, \mu\text{m}$
- NA = 0.102
- DOF = $4.5\, \mu\text{m}$
Holographic projection lithography
Screening

Binary object

Fresnel propagation
(cont. tone hologram)

Half-toning

Binary hologram

Reconstruction
Computer Generated Hologram - dithering
Computer Generated Hologram
Computer Generated Hologram

\[ \lambda = 46.9 \text{nm} \]
\[ \text{pix size} = 50 \text{nm} \]
\[ \text{Field} = 325 \mu\text{m} \]
\[ Z = \sim 250 \mu\text{m} \]
\[ \text{NA} = \sim 0.6 \]
\[ \text{Res} = \sim 82 \text{nm} \]
\[ \text{DOF} = \sim 143 \text{nm} \]

Numerical reconstruction of a CGH
Reconstruction in a photoresist
Summary

• Non-periodic features,
• Simple system,
• Small areas,
• Size is the limitation practical limit,
• Impractical for nanofabrication
Generalized Talbot imaging lithography
Generalized Talbot Imaging lithography

\[ z_T = 2M \frac{p^2}{\lambda} \]

• H. F. Talbot, "Facts relating to optical science" No. IV, Philos. Mag. 9, 401 (1836).
• F.R.S Rayleigh, "On copying diffraction gratings and on some phenomenon connected therewith“, Philos. Mag. 11, (1881).
Previous results

Talbot Mask

1st Talbot Plane

2nd Talbot Plane

3rd Talbot Plane

4th Talbot Plane

5th Talbot Plane
High NA GTI Lithography

\[ \Delta = 0.61 \frac{\lambda}{NA} = 0.61 \lambda \sqrt{1 + \left( \frac{z_T}{W} \right)^2} \]

\[
\begin{align*}
W &= 600 \mu m \\
\Delta &= 99.5 nm \\
W &= 1000 \mu m \\
\Delta &= 63.8 nm
\end{align*}
\]
High NA GTI Lithography
High NA GTI Lithography
Demagnified Generalized Talbot imaging lithography
De-magnified Talbot Imaging

Mask

Talbot planes

Concave mirror

Illumination scheme
De-magnified Talbot Imaging: Schematic

\[ p' = p \left[ \frac{z}{(f - s)} \right] \]

\[ z_T = \frac{2np^2(f - s)}{2np^2 + \lambda(f - s)} \]
De-magnified Talbot Imaging: Experimental setup

EUV Laser
De-magnified Talbot Imaging: Results

\[ \frac{p'}{p} = 0.98 \]

\[ \frac{p'}{p} = 0.887 \]

\[ \frac{p'}{p} = 0.867 \]
De-magnified Talbot Imaging: Results cont.

Reconstruction with de-magnification

Reconstruction without de-magnification
De-magnified GTI: Summary

Comparison between measured and calculated values of de-magnification

<table>
<thead>
<tr>
<th>Calculated de-mag.</th>
<th>Measured de-mag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.96</td>
<td>0.980</td>
</tr>
<tr>
<td>0.86</td>
<td>0.887</td>
</tr>
<tr>
<td>0.82</td>
<td>0.865</td>
</tr>
</tbody>
</table>
De-magnified GTI: Limitation to de-magnification

De-magnified GTI: Limitation to de-magnification

\[ NA = \sqrt{1 + \left( \frac{2(f-s)p^2mf}{(2p^2m + \lambda(f-s))(f-d-s)W} \right)^2}^{\text{-1}} \]

\[ \Delta = 0.61 \frac{\lambda}{NA} \]
Defect tolerance in the Generalized Talbot imaging lithography
Typical Defects in a Mask

Mask with a defect: Numerical Simulation

\[ u(x) = i \frac{e^{\frac{ikx^2}{z}}}{\lambda z} \cdot \int_{-\infty}^{\infty} \hat{u}(\xi)e^{\frac{ik(x-\xi)^2}{z}} d\xi \]
Experimental Verification:
Mask Design
Generalized Talbot Imaging: Defect Tolerance
Experimental Verification: Results for 0.01% and 1% of defect concentration

0.01%

1%

Atomic Force Microscope Scan of patterned resist (PMMA) 20x20micron²
Experimental Verification: Results for 1% of defect concentration

Electron Microscope Scan of patterned resist (PMMA)
Defect concentration

5%

10%

20%
Analysis of the replica quality for different defect concentration

\[
\gamma(u,v) = \frac{\sum_{x,y} [f(x,y) - \tilde{f}_{u,v}] [t(x-u, y-v) - \tilde{t}]}{\left\{ \sum_{x,y} [f(x,y) - \tilde{f}_{u,v}]^2 \sum_{x,y} [t(x-u, y-v) - \tilde{t}]^2 \right\}^{0.5}}
\]

<table>
<thead>
<tr>
<th>Defect concentration</th>
<th>0.01%</th>
<th>1%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simul.</td>
<td>0.89</td>
<td>0.88</td>
<td>0.88</td>
<td>0.86</td>
<td>0.81</td>
</tr>
<tr>
<td>Exp. (mean)</td>
<td>0.93</td>
<td>0.90</td>
<td>0.84</td>
<td>0.86</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Technique Summary

• Optical imprint lithography
• Non contact
• High fidelity
• High resolution
• Size scalable
• Defect tolerant
Functionalization of the nanostructures: Sacrificial mask method

Deposition of a thin metallic layer

Argon plasma etching

EUV-L

Developing

Metallic nanostructure
Functionalization of the nanostructures: Sacrificial mask method

Silver on silicon
Functionalization of the nanostructures: Sacrificial mask method

Gold on silicon
Summary

• Holographic lithography
• GTI
• DGTI
• Defect Tolerance
• Optical imprint technique for mask copying


US Patent

Non-contact, scalable And Defect Free Optical Nano-patternning By Demagnified Talbot Effect,

Conferences


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Best Poster Award Colorado Photonics Industry Assoc. 2009
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References (viewgraph 7)


Thank you