Coherent EUV lithography with Capillary Discharge Laser

Lukasz Urbanski, Apr 6 2012
Outline

• Introduction
  • Laser description
  • Lithography schemes in the past

• Work done so far
  1. Holographic projection lithography
  2. Generalized Talbot Imaging lithography
  3. De-magnified Generalized Talbot Imaging lithography
  4. Defect Tolerance in Generalized Talbot Imaging

• My TO DO list

• Summary
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

Essentially full spatial coherence is achieved increasing the capillary length

Characterization of spatial coherence:
Young’s interferometer

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

Nanoscale coherent lithography with table top EUV lasers

Interferometric lithography

Holographic projection lithography

Generalized Talbot Imaging lithography
Work done so far
Mask Fabrication: Preparation

1. Silicon Nitride Membrane
2. Spin Coating w. Resist & ESPACER
3. E-beam lithography
4. Developing
5. Diffractive Mask
Mask Fabrication EBL

http://www.cnf.cornell.edu/image/spiefig1.jpg
1. Holographic projection lithography

Binary object

Fresnel propagation (cont. tone hologram)

Half-toning

Binary hologram

Reconstruction
Holographic projection lithography

Binary objects and corresponding binary CGHs

Illumination scheme

- Sample
- Hologram
- EUV laser

λ=46.9nm
Pixel Size=140nm
Z=500μm
Field=102.9μm
NA=0.102
DOF=4.5μm
Holographic projection lithography
2. Generalized Talbot Imaging lithography

- H. F. Talbot 1836 "Facts relating to optical science" No. IV, Philos. Mag. 9
- Lord Rayleigh 1881 "On copying diffraction gratings and on some phenomenon connected therewith" Philos. Mag. 11
Previous results

Talbot Mask
1st Talbot Plane
2nd Talbot Plane
3rd Talbot Plane
4th Talbot Plane
5th Talbot Plane
3. De-magnified Talbot Imaging

Concave mirror

Mask

Talbot planes

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
De-magnified Talbot Imaging: Results

\[ p'/p = 0.98 \]

\[ p'/p = 0.887 \]

\[ p'/p = 0.867 \]
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

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

\[ \Delta = k_1 \frac{\lambda}{NA} \]

4. Generalized Talbot Imaging: Defect Tolerance

1-3 Talbot Planes

Diffractive Mask

Talbot Distance: $z_T$
Typical Defects in a Mask


My Experience
Defected Mask: Numerical Simulation
Experimental Verification:
Mask Design
Experimental Verification: Setup
Experimental Verification: Results

Atomic Force Microscope Scan of patterned resist (PMMA) 20x20micron²
Experimental Verification: Results

Electron Microscope Scan of patterned resist (PMMA)
Unit cell-sized defect vs. Healthy mask @ Talbot plane
My TO DO List

1. Randomly Distributed Defect Analysis in GTI,
   a) Analysis and Uniform Description of Defect Tolerance,
2. High NA GTI,
3. CGH Reconstruction.
1. Randomly Distributed Defect Analysis in GTI
Randomly Distributed Defect Analysis in GTI
2. High NA GTI Lithography
2. Possible Applications
3. Computer Generated Hologram Reconstruction
Computer Generated Hologram
Computer Generated Hologram

CFN 5.0kV 9.3mm x600 SE(U,LA0) 10/20/2010

CFN 3.0kV 8.8mm x11.0k SE(M,LA0) 10/20/2010

CFN 3.0kV 8.7mm x22.0k SE(M,LA0) 10/20/2010

CFN 3.0kV 8.8mm x60.0k SE(M,LA0) 10/20/2010
Computer Generated Hologram

λ=46.9nm
pix size: 25nm
Filed: 162.5µm
Wd: 250µm
NA: 0.325
Res: 88nm
DOF: 444nm

Numerical reconstruction of a CGH
Computer Generated Hologram: Experimental Setup
Summary: Publications, Conferences & Awards

Publications


Conferences


Awards

- Best Poster Award Colorado Photonics Industry Assoc. 2010,
- Best Poster Award Colorado Photonics Industry Assoc. 2009
Acknowledgements

♥ Małgorzata Urbańska,
• Prof. Mario Marconi,
• Prof. Carmen Menoni,
• Prof. Vakhtang Putkaradze,
• Prof. Randy Bartels,
• Илья Кузнецов (Ilya Kuznetsov ),
• 李炜 (Wei Li),
• Nils Monserud,
• Christopher Brown,
• Erik Malm.
Dessert

Splash One. 
Attempt of electroplating gold onto a patterned resist.

The Persistence of Charge. 
SEM imaging of thick ZEP520 resist
Repetitive operation generates high average powers

3.5 mW Average Power Demonstrated at 46.9 nm
(0.88 mJ/pulse at 4 Hz)

Other Laser Output Parameters:
• Peak Power : 0.6 MW
• Pulsewidth : 1.2 - 1.5 ns
• Beam divergence : 4.6 mrad
Experimental Verification: Analysis

\[ u = \frac{2\pi}{\lambda} \left( \frac{a}{r} \right)^2 z, \quad r = \frac{2\pi}{\lambda} \sqrt{x^2 + y^2} \]

\[ U(P) = -\frac{i}{\lambda} A \int_C \left( \int_{\Omega} e^{-i\mathbf{q} \cdot \mathbf{R}} d\Omega \right) \]

\[ U(P) = -\frac{2\pi i a^2 A}{\lambda f^2} e^{i \left( \frac{f}{a} \right) u} \int_0^1 J_0(\nu \rho) e^{-i u \rho^2} \rho d\rho. \]

\[ 2 \int_0^1 J_0(\nu \rho) e^{-i u \rho^2} \rho d\rho = C(u, v) - i S(u, v), \]

\[ C(u, v) = 2 \int_0^1 J_0(\nu \rho) \cos \left( \frac{1}{2} u \rho^2 \right) \rho d\rho, \]

\[ S(u, v) = 2 \int_0^1 J_0(\nu \rho) \sin \left( \frac{1}{2} u \rho^2 \right) \rho d\rho. \]
Experimental Verification: Analysis

\[ U_n(u, v) = \sum_{s=0}^{\infty} (-1)^s \left( \frac{u}{v} \right)^{n+2s} J_{n+2s}(v), \]

\[ V_n(u, v) = \sum_{s=0}^{\infty} (-1)^s \left( \frac{v}{u} \right)^{n+2s} J_{n+2s}(v), \]

Distribution of Intensity

\[ I(u, v) = \left( \frac{2}{u} \right)^2 \left[ U_1^2(u, v) + U_2^2(u, v) \right] I_0, \]
Experimental Verification: Analysis

Special Cases:

Special case: Intensity on axis

\[ d = 1.9 \sqrt{f \lambda} \]

Example:
Focus produced by a 5 micron opening illuminated with 46.9nm light

\[ f = \frac{d^2}{(1.9)^2 \lambda} \]

f = 0.125mm
a = 0.005mm
NA = 0.0200
DOF = 0.117mm
Experimental Verification: Analysis

1st Talbot Plane

DC

$z_T$

$f$
Diffraction pattern vs. Coherence radius

Figure 5-23. Diffraction pattern of a circular aperture for various states of transverse coherence. The parameter $C$ represents the ratio of the area of the circular aperture to a coherence area. A circular incoherent source was assumed. The variable $x$ has been normalized. (Ref. 5-34). (Courtesy of B. J. Thompson and the Optical Society of America.)
\[ \mathcal{Q}[c]\{U(x)\} = e^{j\frac{k}{2}cx^2} U(x), \]
\[ \mathcal{V}[b]\{U(x)\} = b^{1/2} U(bx), \]
\[ \mathcal{R}[d]\{U(x_1)\} = \frac{1}{\sqrt{j\lambda d}} \int_{-\infty}^{\infty} U(x_1) e^{j\frac{k}{2d}(x_2-x_1)^2} dx_1, \]
\[ S = R[f - s - z] \cdot Q \left\{ \frac{1}{z} \right\} = \]

\[ \left\{ \begin{array}{c}
R[d] \cdot Q[c] = Q \left[ (c^{-1} + d)^{-1} \right] \\
\cdot V \left[ (1 + cd)^{-1} \right] \\
\cdot R \left[ (d^{-1} + c)^{-1} \right]
\end{array} \right\} \]

\[ = Q \left[ \frac{1}{(f - s)} \right] \cdot V \left[ \frac{z}{(f - s)} \right] \cdot R \left[ \frac{(f - s - z)z}{(f - s)} \right] \]

\[ U(x) = \exp \left[ \frac{ik}{2} cx^2 \right] \int_{-\infty}^{\infty} \left( x_{1} \frac{z}{(f - s)} \right) \exp \left[ \frac{ikz(x_{1} - x)^2}{2(f - s - z)(f - s)} \right] dx_{1} \]
\[ U_{TOT}(x) = D(x) + \sum_{m} A_{m} \exp \left( 2\pi i m \frac{x}{p} \right). \]

\[ \tilde{U}_{TOT}(\nu, z = 0) = \tilde{d}(\nu, z = 0) + A_{0} \delta(\nu) + \sum_{m \neq 0} A_{m} \delta(\nu - m \nu_{0}) \]
\[ = \tilde{d}(\nu, z = 0) + A_{0} \delta(\nu) + \tilde{u}(\nu, z = 0). \]

\[ \tilde{U}_{TOT}(\nu, z) = \tilde{d}(\nu, 0) + A_{0} \delta(\nu) + \sum_{m \neq 0} A_{m} \exp \left( -2i \pi m^{2} \frac{z}{\nu_{0} z_{T}} \right) \delta(\nu - m \nu_{0}). \]

\[ U_{TOT}(x, z) = D(x, z) + A_{0} + \sum_{m \neq 0} A_{m} \exp \left[ -2i \pi \left( \nu_{0} x - m^{2} \frac{z}{\nu_{0} z_{T}} \right) \right] \]
\[ = D(x, z) + U(x, z + N z_{T}). \]
Spatial and Temporal Coherence

Mutual coherence factor

\[ \Gamma_{12}(\tau) \equiv \langle E_1(t + \tau)E_2^*(t) \rangle \]  

(8.1)

 Normalize degree of spatial coherence (complex coherence factor)

\[ \mu_{12} = \frac{\langle E_1(t)E_2^*(t) \rangle}{\sqrt{\langle |E_1|^2 \rangle} \sqrt{\langle |E_2|^2 \rangle}} \]  

(8.12)

A high degree of coherence (\( \mu \to 1 \)) implies an ability to form a high contrast interference (fringe) pattern. A low degree of coherence (\( \mu \to 0 \)) implies an absence of interference, except with great care. In general radiation is partially coherent.

Longitudinal (temporal) coherence length

\[ \ell_{\text{coh}} = \frac{\lambda^2}{2 \Delta \lambda} \]  

(8.3)

Full spatial (transverse) coherence

\[ d \cdot \theta = \frac{\lambda}{2\pi} \]  

(8.5)