PhD Preliminary Exam

EUV Technology and Applications

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Outline

EUV Technology and applications

– Motivations
  • EUV region of EM spectrum and EUV sources
  • EUV applications
  • Source: 46.9 nm discharge pumped table top laser

– Nanopatterning using Interference Lithography
  • Previous work
  • Compact tool
  • Printing different motifs
  • Photo-resists: PMMA and HSQ

– Table top extreme ultraviolet holography
  • Previous work
  • Setup description
  • Results
  • Resolution estimation
  • Parameters limiting the resolution

– Future work

– Summary and conclusions
Motivations

Electromagnetic Spectrum

Well known region

Still unexplored

- wavelength coincides with atomic and molecular resonance frequencies – very high absorption, almost everything is opaque
- difficult to find appropriate optics to change the beam properties
- lack of accessible coherent sources

Why to use EUV?
- shorter wavelength – better resolution
  
\[ k \cdot NA \cdot \lambda \delta = \]

- different material properties at that wavelength (i.e. \( n < 1 \))

SiO\(_2\) 100nm thick
EUV Sources

Synchrotrons:

Advantages:
• tunable wavelength of the beam
• high flux

Disadvantages:
• pretty big facilities,
• not easily accessible
• low coherence, if not filtered
• multi-milion $ facility

EUV Plasma Sources:

Advantages:
• small, easy to move,
• high power,
• cheaper than synchrotrons
• one can buy one –
  - accessible

Disadvantages:
• not monochromatic,
• emission in large solid angle – impossible to collect all light
• not coherent

Energetiq plasma source
Discharge pumped EUV lasers:

**Advantages:**
- lasers – so are *highly coherent* (spatial and temporal) – good or specific applications
- **small** – table-top or even desk-top
- easy to access and relatively cheap
- **high energy** per pulse (~0.8mJ/pulse) – max
- very robust, low maintenance required,

>>> Very useful for my applications <<<
Capillary discharge laser – 46.9 nm

- High fluence
- mW average power
- Repetition rate: 4 Hz
- High energy per pulse max - 0.8 mJ
- Average power ~ 3 mW
- High monochromacity: $\Delta \lambda / \lambda = 1 \times 10^{-4}$
- Coherence radius: $R_c = 550 \, \mu m$
  at 0.157m from 36cm capillary
- Very compact


Some applications of EUV light

- **EUV Microscopy**
  
  38nm resolution with 13.2nm Cd laser, ~70% modulation

  “Sub-38 nm resolution tabletop microscopy with 13 nm wavelength laser light” Vaschenko at. al., OPTICS LETTERS / Vol. 31, No. 9 / May 1, 2006

- **EUV Interferometry of dense plasmas**

  “Dense plasma diagnostics with an amplitude-division soft-x-ray laser interferometer based on diffraction gratings”, J. Filevich, et. al., OPTICS LETTERS / Vol. 25, No. 5 / March 1, 2000

- And many more…
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Nanopatterning using Interference Lithography

Previous Work in Interferometric Lithography include:

**Ar, F₂ and ArF lasers. Multiple exposures, immersion lithography:**

**Synchrotron radiation:**

*And many, many more.....*
Interferometric Lithography
Periodic features

Interference creates an intensity modulation in the region of the overlapping of two or more coherent beams.

Advantages:
• period limited mainly by $\lambda$
• parallel imprint process
• possible to write really small features
• simple scheme

Requirements:
• high spatial and temporal coherence of the source

Applications:
• characterization of photoresist
• production of nanochannel devices
• potential for fabrication of nanomagnetic structures

Two beams with the same wavelength:

$$p = \frac{\lambda}{2 \sin(\Theta)}$$
Photoresist is a **light-sensitive polymer** used to form a patterned coating on a surface.

**Positive**

- UV, EUV light
- Mask
- Photoresist
- Substrate

Exposed portion of the photoresist is soluble to the developer

**Negative**

- UV, EUV light
- Mask
- Photoresist
- Substrate

Exposed portion of the photoresist remains after developing

**PMMA** - Polymethyl methacrylate

**HSQ** - Hydrogen silsesquioxane
Table top Nanopatterning – Compact tool

Double exposure set up with a Lloyd’s mirror

Schematic of compact patterning tool

Two successive exposures allows printing arrays of nanometer size features
Nanopatterning tool

Experiment chamber

Motorized pivoting platform

Motorized rotation stage

Motorized translation stage

Sample

Capillary discharge laser

Laser beam

Cr Mirror

Photograph of the Nanopatterning tool

Mirror reflectivity vs. angle

$\theta$ [deg]
Coherence limitations to the printing area

- Spatial coherence:
  
  \[ D \leq 2R_c \]
  
  \[ x = \frac{R_c}{\cos(\Theta)} \]

- Temporal coherence:
  
  \[ b - a \leq l_c \]
  
  \[ x = \frac{l_c}{2 \sin(\Theta)} \]

Radius of coherence: \( R_c \sim 0.5 mm \)

Coherence length:

\[ l_c = \frac{\lambda^2}{\Delta \lambda} = 469 \mu m \]
This approach allows to pattern areas typically $500 \times 500 \mu m^2$.

The pattern shape can be controlled by:
1. **Changing the exposure dose** – pillars or holes
2. **Changing the angle between exposures** ($\alpha$) – changes the geometry of the pattern
3. **Changing the interferometer angle** ($\theta$) – changes the period in each exposure
Different motifs – pillars or holes

Calculated pillar array with $\alpha = 90^0$
Not activated region

Pillars with FWHM down to 58 nm (1.2$\lambda$) were obtained with period 153nm at high dose

Fabricated array at 166mJ/cm$^2$

Feature size was close to the wavelength limit $\lambda = 46.9$nm

Calculated hole array with $\alpha = 90^0$
Activated region

Holes were obtained at the low dose with FWHM ~60 nm

Fabricated array at 110mJ/cm$^2$
Different motifs – ovals

Different rotation angles allows printing different motifs

Calculated array with $\alpha = 30^0$

Pillars - FWHM $80 \times 160 \text{ nm}^2$
were obtained at the high dose with periods $160 \text{nm}$ and $320 \text{nm}$

Fabricated array

Calculated array with $\alpha = 90^0$

Pillars FWHM $75 \times 110 \text{ nm}^2$
(1.6x2.3)$\lambda$ were obtained with holes between ~$60 \text{nm}$ diameter

Fabricated array
Smallest features

**Pillars**

- Period **90nm**
- Pillars FWHM ~**45nm**

**Lines**

- Period **95nm**
- Lines FWHM ~**47nm**
Large areas

**Period 140nm**,  
pillars FWHM \(\sim 70\text{nm}\)  
Scan size 10x10\(\mu\text{m}^2\)

**Period 95nm**,  
lines FWHM \(\sim 47\text{nm}\)  
Scan size 7x7\(\mu\text{m}^2\)
Table top Nanopatterning - HSQ photoresist

Why HSQ?

**HSQ** - hydrogen silsesquioxane has some advantages over the PMMA photoresist:

- The penetration depth at 46.9nm wavelength is more than **150nm** (due to the chemical composition - H, O, Si)
- More resistant to ion beam etching: 1.22nm/s for PMMA, **0.47nm/s** HSQ with the same etching parameters
- High spatial resolution ~**10nm**.
- Requires less dose for activation than PMMA

Attenuation lengths (1/e) for 30eV radiation (\(\lambda \approx 41.3\)nm)

www.cxro.lbl.gov

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Different motifs with HSQ

106nm width lines patterned in HSQ photoresist

Dose: $\sim 41 \text{mJ/cm}^2$

130nm diameter holes patterned in HSQ, depth $\sim 110 \text{nm}$

Dose: $\sim 41 \text{mJ/cm}^2$
Large arrays of holes

120nm depth, ≈100nm FWHM
Scan size 20x20µm², dose ~80mJ/cm²
Holes or Pillars

For PMMA:

\[ \text{Dose} \approx 41 \text{mJ/cm}^2 \]
\[ \approx 110 \text{mJ/cm}^2 \]

\[ \approx 166 \text{mJ/cm}^2 \]
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Previous work

Milestones in holography:


And many, many more…..
EUV Holography Setup

**Object characteristics:**

**Tip characteristics (according manufacturer):**
- cantilever length $l = 230 \mu m$
- width $w = 40 \mu m$
- thickness $t = 7 \mu m$
- full tip cone angle $a = 30^\circ$
- tip height $h = 20 - 25 \mu m$
- typical tip curvature radius $r$ of uncoated probe $< 10.0 \text{ nm}$

AFM digitized holograms and reconstructions

- Hologram and reconstructed image obtained at $z_p = 4\text{mm}$, digitized with AFM, pixel size = 270nm

- Hologram and reconstructed image obtained at $z_p = 120\mu\text{m}$, digitized with AFM, pixel size = 41nm

10-90% max ~ 160 nm
Method of Resolution estimation

Hologram and reconstructed image obtained at $z_p = 120\,\mu m$, digitized with AFM, pixel size = 41 nm

Correlation coefficients vs. wavelet order

Hologram and reconstructed image obtained at $z_p = 120\,\mu m$, digitized with AFM, pixel size = 41 nm
Correlation Analysis Results

- $z_p \sim 4\text{mm}$
  - pixel size: $270\text{nm}$
  - optimum reconstruction $z_p = 4.04 \text{ mm}$
  - resolution: $2^{0.5} \cdot 270\text{nm} = 381\text{ nm}$

- $z_p \sim 120\mu\text{m}$
  - pixel size: $41\text{nm}$
  - optimum reconstruction $z_p = 124 \mu\text{m}$
  - resolution: $2^2 \cdot 41\text{nm} = 164\text{ nm}$
Resolution due to EUV laser coherence parameters

Coherence limitations:
- spatial coherence
- temporal coherence

\[ NA_{\text{max}} = \sin \left( \alpha \tan \left( \frac{R_c}{z_p} \right) \right) \]

\[ \delta = \frac{0.61 \lambda}{NA_{\text{max}}} \]

Rayleigh criterion for resolution

<table>
<thead>
<tr>
<th>Table with resolutions for…</th>
<th>Transversal coherence</th>
<th>Longitudinal coherence</th>
<th>Experimental resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z_p = 4 \text{ mm} )</td>
<td>( 337.8 \text{ nm} )</td>
<td>( 64.1 \text{ nm} )</td>
<td>( 381 \text{ nm} )</td>
</tr>
<tr>
<td>( z_p = 120 \text{ ( \mu \text{m} )} )</td>
<td>( 30.4 \text{ nm} )</td>
<td>( 29.2 \text{ nm} )</td>
<td>( 164 \text{ nm} )</td>
</tr>
</tbody>
</table>

Hologram scanning limitations:

\[ N_{\text{total}} = \left( \frac{N_{\text{samples}}}{\text{line}} \right)^2 \sim \left( \frac{\lambda \cdot z_p}{\delta^2} \right)^2 \]

\[ NA = \sin \left( \alpha \tan \left( \frac{d}{z_p} \right) \right) \]

\[ NA \leq NA_{\text{max}} \]

If \( \delta = \lambda = 46.9 \text{ nm}, \) at \( z_p = 4 \text{ mm}, \)
\[ N_{\text{total}} = 7.27G \text{ samples} \]

Real limitation to the resolution.
\( z_p \) has to be smaller.

July 11, 2007
Future work

- Transferring the pattern to metallic substrates

- Nanopatterning using plasmonic resonances

- Nanopatterning of magnetic materials

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**CAIBE**

46.9 nm EUV

**HSQ**

Metal, Ag

Quartz

Fused silica

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Mask made with CDL $d << \lambda_{vis}$

**PMMA**

**Si**

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Cap

Free

Spacer

Fixed

Base electrode

2nm Cu/3.5nm Pd
4.5nm Ni$_{80}$Fe$_{20}$
6nm Cu
20nm Co$_{81}$Fe$_{19}$
5nm Pd/25nm Cu

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"Phase-locking in double-point-contact spin-transfer Devices", F. B. Mancoff et. al., NATURE, vol 437, 15 September 2005
Summary - Nanopatterning

Table top EUV laser sources enables table top nanopatterning tool:

- Compact and reliable set up,
- Sub-60nm features were patterned,
- Versatile: printing different periodic motifs,
- Very short exposure times,
Summary - EUV Holography

- **Sub-200 nm** resolution in the recording and reconstruction of a holographic image obtained in the Gabor’s geometry with a table top EUV laser was demonstrated,

- Demonstrated resolution analysis shows that the temporal and spatial coherence of the 46.9 nm laser do not limit the NA of the hologram allowing for **sub 100 nm** resolution,

- To determine the optimum reconstruction parameters and assess the spatial resolution of the holographic recording we used a wavelet decomposition and correlation analysis,
Thank you

List of publications

Journal publications:

Conference Proceedings:
1. "Table top EUV holography with sub 200 nm spatial resolution", Przemyslaw Wachulak, Mario C. Marconi, Randy A. Bartels, Carmen S. Menoni, Jorge J. Rocca, SPIE Proceedings, 26 - 30 August 2007, San Diego 6702-18
2. "Interferometric lithography with sub 100 nm resolution using a table top $\lambda=46.9$ nm laser" Mario C. Marconi, Przemyslaw Wachulak, Dinesh Patel, Maria Gabriela Capeluto, Carmen S. Menoni, Jorge J. Rocca, SPIE Proceedings, 26 - 30 August 2007, San Diego, 6702-17