Soft X-ray Emission from Alexandrite Laser-Matter-Interaction

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# Soft X-ray Emission from Alexandrite Laser-Matter-Interaction

X-ray spectroscopy was used to quantify the plasma generated by a focused, Alexandrite laser as a potential alternative source in proximity lithography. An x-ray emission efficiency of 2 - 11% was determined by analysis of spectral data (10 - 14Å) from transition-metal targets.
SOFT X-RAY EMISSION FROM ALEXANDRITE LASER-MATTER-INTERACTION

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Manuscript approved June 6, 1993.
EXPERIMENTAL

A compact (table-top), focused Alexandrite (750 nm) pulsed-laser system generated soft x-ray emission from planar-metal targets. Quantitative x-ray spectroscopy (active and passive detection) and pinhole imagery were used to characterize the 10 - 14 Å region that is important for resist exposure in proximity x-ray lithography. X-ray data was collected from transition metal targets. The spectra, acquired on film, were densitometered and computer processed to obtain line intensities from the L-shell transitions in highly-ionized copper and iron plasma. Spectral data was also acquired from K-shell transitions in aluminum in order to compare the effects of less than 8 Å spectral wavelengths (>1.5 keV energy) as the more energetic x-rays have greater penetration in the lithographic process.

The 10 Hz Alexandrite laser system at Allied Signal employs a Ti: sapphire oscillator, a pulse-stretcher (grating-pair), and a three-stage Alexandrite regenerative amplifier stage. The laser can generate chirped pulses (0.75 ns) up to 1 joule. These pulses can be recompressed to shorter pulse widths with an additional grating pair. Spectral data was acquired with both single laser pulses and a train of widely-spaced (8-ns) laser pulses.
1 Joule, 1 ns, 10 Hz alexandrite laser
5 to 3 amplifiers

Stretcher

15 mJ 1x D.L.

Ti:sapphire Oscillator

50 mJ 1x D.L.

Alexandrite amplifier #1

250 mJ 2x D.L.

Alexandrite amplifier #2

1.0 J 6x D.L.

Alexandrite amplifier #3

x-ray lithography,
DARPA, MXR
ALEXANDRITE FOCUSED LASER

ALLIED-SIGNAL Corp.
Morristown, NJ

Wavelength: 800 nm
Pulse Energy: 1 J
Pulserwidth: 3/4 ns
Repetition Rate: 10 Hz
X-RAY PINHOLE IMAGES

for

ALEXANDRITE LASER
X-RAY EXPOSURE
UNIFORMITY

Curved-Channel Plate Array Camera
SPECTRA
from
ALEXANDRITE LASER
Neon-like Copper
Cu XX

Intensity(eV/sr-Å)

Wavelength(Å)

2p-6d 2p-5d 2p-4d 2s-3p 2p-3d 2p-3s

10/1/92:2030, Allied Signal, Cu Disk, 500mJ, 300sh
Neon-like Iron
Fe XVII

Intensity (eV/sr-Å)

Wavelength (Å)

10/1/92:2200, Allied Signal, Fe target, 250μJ, 300sh
Table I. X-Ray Spectral Intensities Generated by Alexandrite Laser.

<table>
<thead>
<tr>
<th>Target Material</th>
<th>Shot Sequence</th>
<th>Number of Shots</th>
<th>Spectral Range Angstrom</th>
<th>Integrated Intensity eV/sr</th>
<th>Output Joules into $2\pi$</th>
<th>Output mJ/shot into $2\pi$</th>
<th>$\eta, %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>10/1/92:1400</td>
<td>400</td>
<td>7-14</td>
<td>$1.89 \cdot 10^{18}$</td>
<td>1.9</td>
<td>4.8</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>10/1/92:1500</td>
<td>270</td>
<td>7-14</td>
<td>$3.74 \cdot 10^{18}$</td>
<td>3.8</td>
<td>14.1</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>10/1/92:1630</td>
<td>300</td>
<td>7-14</td>
<td>$3.75 \cdot 10^{18}$</td>
<td>3.8</td>
<td>12.7</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>10/1/92:2030</td>
<td>300</td>
<td>7-14</td>
<td>$4.98 \cdot 10^{18}$</td>
<td>5.0</td>
<td>16.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Fe</td>
<td>10/1/92:2130</td>
<td>300</td>
<td>9-18</td>
<td>$7.86 \cdot 10^{18}$</td>
<td>7.9</td>
<td>26.3</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>10/1/92:2200</td>
<td>300</td>
<td>9-18</td>
<td>$8.54 \cdot 10^{18}$</td>
<td>8.6</td>
<td>28.7</td>
<td>11.5</td>
</tr>
</tbody>
</table>
X-RAY SPECTRAL DATA
for LASER PULSE TRAIN
### Soft X-Ray Output

<table>
<thead>
<tr>
<th>Data Group</th>
<th>Energy on Copper Target</th>
<th>Number shots</th>
<th>X-Ray Intensity (eV/sr)</th>
<th>Pulse Shape</th>
<th>Emission Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct.</td>
<td>1/2 J</td>
<td>300</td>
<td>$4.8 \times 10^{18}$</td>
<td>a)</td>
<td>unity</td>
</tr>
<tr>
<td>Dec.</td>
<td>1 J</td>
<td>120</td>
<td>$1.1 \times 10^{18}$</td>
<td>b)</td>
<td>less by 2x</td>
</tr>
<tr>
<td>Dec.</td>
<td>2/5 J</td>
<td>120</td>
<td>$0.46 \times 10^{18}$</td>
<td>c)</td>
<td>less by 4x</td>
</tr>
</tbody>
</table>

a) single pulse 3/4 ns width  
b) train of pulses with 1 J leading edge  
c) train of equal-intensity pulses separated by 8 ns
X-RAY SOURCE TRANSMISSION
for LITHOGRAPHY

A. X-RAY MASKS + SUBSTRATE
B. X-RAY RESISTS
Transmission of Thin Membranes

Transmission

Photon Energy (eV)

- 0.5 μm C₃H₆
- 0.5 μm Si
- 0.5 μm SiC
- 0.5 μm Diamond
- 0.5 μm Si₃N₄
- 8.46 μm Be
# Soft X-Ray Spectral Transmission

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Region</th>
<th>Source Strength</th>
<th>Helium Path</th>
<th>Substrate Mask, SiC</th>
<th>Helium Path &amp; Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Å)</td>
<td>(eV/sr)</td>
<td>1 atm 20-cm</td>
<td>1-µm</td>
<td>2-µm</td>
</tr>
<tr>
<td>Cu L</td>
<td>7-14</td>
<td>$4.0 \cdot 10^{18}$</td>
<td>84%</td>
<td>63%</td>
<td>40%</td>
</tr>
<tr>
<td>Fe L</td>
<td>8-17</td>
<td>$9.9 \cdot 10^{18}$</td>
<td>71%</td>
<td>43%</td>
<td>18%</td>
</tr>
</tbody>
</table>
X-Ray Transmission for PMMA with 15% ZnI₂ Added

Resist Thickness (μm) |
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>5.0</td>
</tr>
</tbody>
</table>

Photon Energy (eV)

Transmission

0.0  0.2  0.4  0.6  0.8  1.0

22
X-Ray Transmission for Multilayer Resists

![Graph showing X-ray transmission for multilayer resists. The graph plots transmission against photon energy (eV). There are multiple curves representing different resist formulations: PMMA alone, PMMA + C₆H₅Si, PMMA + C₆H₅BrSi.](image)
<table>
<thead>
<tr>
<th></th>
<th>Resist PMMA (μA/cm²)</th>
<th>Mask Substrate (μA/cm²)</th>
<th>Source Emission (μA/cm²)</th>
<th>Target Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.022</td>
<td>0.024</td>
<td>0.037</td>
<td>Aluminum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>0.324</td>
<td>0.415</td>
<td>0.648</td>
<td>Iron</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table II. Soft X-Ray Transmission.
<table>
<thead>
<tr>
<th>Target Material</th>
<th>PMMA (J/cm²)</th>
<th>+15% ZnI (J/cm²)</th>
<th>Multilayer (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resist Exposure (J/cm²)</td>
<td>4.84 \times 10^{-4}</td>
<td>8.45 \times 10^{-4}</td>
<td>1.23 \times 10^{-3}</td>
</tr>
<tr>
<td>6.00 \times 10^{-5}</td>
<td>2.29 \times 10^{-4}</td>
<td>4.67 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>1.04 \times 10^{-3}</td>
<td>3.63 \times 10^{-4}</td>
<td>9.23 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>1.68 \times 10^{-3}</td>
<td>5.72 \times 10^{-4}</td>
<td>7.13 \times 10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

Table III. Soft X-Ray Absorption.
SUMMARY

The diagnostic instrumentation included filtered-PIN diodes, a diffraction-crystal spectrograph, and a film-recording x-ray pinhole camera. The x-ray spectrograph utilized a curved-KAP crystal.

An x-ray spectrum was recorded from a copper target. The most distinct and intense lines originate from transitions to the L-shell in neon-like copper. Spectral lines occur in the 8 - 14 Å region; however, the strongest lines are 2 - 3 level transitions in the 10 - 14 Å range from fluorine-like Cu XXI and Neon-like Cu XX. For the iron data, the same spectral transitions as in copper are generated but are shifted 3 - 4 Å to longer wavelength.

The x-ray output energy was determined assuming uniform emission over $2\pi$ for the plasma generated at the surface of the planar targets. The soft x-ray conversion efficiency of the focused-laser beam was found to range from 1.9% at $\frac{1}{4}$ J to 3.2% at $\frac{1}{2}$ J integrated over the 10 - 14 Å spectral region with an average efficiency of 2.5% for both copper and iron plasma. The total x-ray emission read in the 7 - 18 Å region is stronger for the iron targets by a factor of 3 because of the intense emission between 14 and 18 Å in neon-like Fe XVII. A soft x-ray conversion efficiency of greater than 10% was recorded for a $\frac{1}{2}$ J iron target shot.
CONCLUSIONS

- **SOURCE STRENGTH**

  Alexandrite laser yields highest efficiency from iron target (L-spectrum) and lowest from aluminum (K-spectrum); however, copper has good L-shell spectral output in the 10 - 14 Å region.

- **LITHOGRAPHIC CONSIDERATIONS**

  Soft X-ray spectral transmission and absorption calculations revealed that the energy deposition into high-Z loaded PMMA resists can achieve greater than 45% soft x-ray deposition for copper and iron L-spectrum but only 20% for the energetic aluminum spectral distribution.