Repetitive Operation of A Dense Plasma Soft X-ray Source for Micromachining

D. Wong, T. L. Tan, A. Patran, S. M. Hassan, T. Zhang, S. V. Springham, S. Lee, R. S. Rawat, and P. Lee

Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University, Singapore

Abstract. The NX2 device, a low energy plasma focus, at the Nanyang Technological University in Singapore, was used as a soft X-ray (SXR) source for micromachining. The gas used was neon which produced SXRs in a narrow spectral range of 0.9 – 1.6 keV. The SXR yield from repetitive operation of the NX2 device was monitored and measured using a cost effective multi-channel SXR spectrometric system. The system consists of filtered BPX65 PIN diodes, with the associated electronics – an integrator, sample and peak holder, analogue switch, an A/D converter and a microcontroller. The system enables easy shot-to-shot statistical analysis under repetitive operation at adjustable preset trigger frequencies. A total of 4000 shots were fired at 0.5 Hz, using the same gas filling. The SXR production was at an average yield of 60 J/shot and a maximum single-shot yield of more than 100 J. The SXRs emitted by the NX2 device was used for contact micromachining, producing structures with an excellent aspect ratio of up to 20:1 on 25 μm SU-8 resist.

Keywords: plasma focus, X-rays, DPF repetitive operation, micromachining, SU-8 resist.

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INTRODUCTION

Various studies on the dense plasma focus (DPF) as a source of soft X-rays (SXRs) for scientific and industrial applications have been performed. For microlithographic applications, neon SXRs with energy ~1 keV seems to be the best choice, where certain commercially available chemically-amplified resists show reasonable sensitivity [1]. In this paper, we demonstrate, for the first time, the use of the DPF for micromachining, with good results.

EXPERIMENTAL SETUP

The experiments were carried out on the NX2: a 27.6-μF, 15-kV, 430-kA DPF device. The details of the device, together with the SXR optimization studies are described elsewhere [2, 3]. The total SXR yield was measured using filtered BPX65 PIN diodes placed 410 mm radially from the anode axis. The schematic of the experimental set-up is shown in Fig 1.
The SXR signals captured by the PIN diodes are integrated and held by a sampling circuit, where an operational amplifier is used for each channel to increase the holding time. The microcontroller reads the signal for each channel sequentially and discharges a capacitor by turning on the corresponding switch in the analogue switch array until all signals from all the channels have been read. These values are then sent to the host computer and can be stored for processing.

The filter characteristics used in the experiments are shown in Table 1. Using well-known Henke’s data for the X-ray attenuation length in solids, the overall transmission curves of the diode-filter detectors were obtained, and are presented in Fig. 2. The difference in the signals between channels 1 and 2 give a measure of the Ne SXR in the 0.9 – 1.6 keV. The other channels are used to give a measure of the Cu K\(\alpha\) radiation in the 7.9 – 8.5 keV region.

### TABLE 1. The filter selection for the X-ray spectrometer.

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter</td>
<td>Al</td>
<td>Mylar</td>
<td>Ni</td>
<td>Co/Be</td>
<td>Mylar</td>
</tr>
<tr>
<td>Thickness/(\mu)m</td>
<td>8</td>
<td>100</td>
<td>7</td>
<td>8/50</td>
<td>2600</td>
</tr>
</tbody>
</table>

![FIGURE 1. The schematic of the experimental set-up.](image1)

![FIGURE 2. The diode-filter sensitivity for 5 channels of the X-ray spectrometer.](image2)

### RESULTS AND DISCUSSION

The firing was done for every 400 shots at 5 min intervals, at 0.5 Hz continuously using the same gas, using water-cooled anodes. We fired a total of 4000 shots and the
average yield was 60 J/shot; the shot-to-shot standard deviation of 20% and the maximum single-shot yield more than 100 J. The percentage of dropouts, defined as plasma discharges that produce less than 10% of the average SXR yield, was only about 0.5%. It can be seen from Fig. 3 that operation in repetitive mode clearly improved the yield jitter. Comparing the standard deviation of the first 10 shots to the last 10 shots for every 400 shots showed that the yield jitter generally decreased by about 10%. This means that the yield can be controlled more precisely than expected from single shot experiments, which is an important advantage for lithographic applications.

For a closer study, we computed the running average yield curves for both Ne SXR and Cu SXR for the first 400 shots. It can be seen from Fig. 3 that it takes an initial ~10 conditioning shots before the yield stabilizes. The results from the continuous 400 shots confirmed that the production of Cu SXR does not continue to increase and remains flat as seen from the running average curve in Fig. 3. Therefore the corresponding Ne SXR production is not seriously affected and likewise remains relatively flat. A maximum of close to about 0.3 J of copper Kα radiation, due to the ablation of the copper anode, was detected.

Although the anode itself was water-cooled, the chamber gets hot, with the top flange reaching to temperatures close to 80°C during repetitive firing. For lithography purposes the SU-8 resist has to be kept at temperature below 90°C. We are able to fire at least 4000 shots while maintaining constant average soft X-ray emission, without the need for gas flow or change. The typical maintenance cycle (limited by the insulator sleeve life span) was longer than 10,000 shots.

We used a 10 μm Be filter over the mask and resist so as shield off visible and ultra-violet rays. This is to ensure that only the SXRs were responsible for the cross-linking of the SU-8 resist. The samples are placed 208 mm axially from the anode tip as shown in Fig.1. In terms of dosage, the 4000 shots corresponded to about an absolute SXR irradiation of 2500 mJ/cm² on the resist surface. The SEM micrograph in Fig. 4 shows test structures successfully imprinted on the SU-8 resist.
Hence this result confirms the reliability of the yield measurements taken from our X-ray spectrometric system.

**FIGURE 4.** SEM test structures on SU-8 resist.

**CONCLUSIONS**

We have demonstrated how the NX2 device can be used as a plasma SXR source in the 0.9 – 1.55 keV for micromachining. It is able to provide optimum dose for SU-8 resist without gas change in 4000 shots. The micromachining test structures showed an excellent aspect ratio of up to 20:1 in 25 μm SU-8 resist. Further studies can be done to optimize the X-ray production in the higher energy range of 2.5-5.0 kV so as to penetrate through thicker layers of resist. Prospective candidates include gases such as argon [4] or xenon. Another interesting possibility is to subject anodes with metal inserts such as aluminium or titanium, under repetitive firing and to investigate if the resulting ablation of the inserts by the runaway electrons will be able to produce enough X-rays resulting from the vapours of the metallic inserts during the pinch.

**ACKNOWLEDGMENTS**

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**REFERENCES**
