Intense plasma discharge source at 13.5 nm for extreme-ultraviolet lithography

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We measured an emission of 6 mJ/pulse at 13.5 nm produced by the Li^{2+} Lyman-α transition excited by a fast capillary discharge, using a lithium hydride capillary. 75% of the energy emanated from a spot size of 0.6 mm. The emission is narrow band and would thus be useful in extreme-ultraviolet lithography imaging systems that use Mo:Si multilayer mirrors. The output within the bandwidth of Mo:Si mirrors was comparable with that of a laser-produced plasma (LPP), and the wallplug efficiency of 0.1% was nearly an order of magnitude better than that of a LPP. © 1997 Optical Society of America

The development of efficient normal-incidence multilayer reflective coatings in the 13–14-nm wavelength region has led to many new optical applications. One of the most demanding applications is extreme-ultraviolet lithography (EUVL). This lithography would use reduction imaging to print microchip features smaller than 0.1 μm. With the use of all-reflective optics (reflectivities up to 65% per surface with Mo:Si multilayer coatings) it should be possible to operate a lithographic stepper in the 13–14-nm wavelength range with the throughput required by a commercial microchip manufacturing system.[1–3] The present sources under consideration for such a system include synchrotrons and laser-produced plasmas (LPP's).[4–7] Although both of these sources have the capability of producing the necessary flux for EUVL, synchrotrons are large and expensive and LPP's are inefficient and costly and have significant debris problems.[8]

It was proposed that doubly ionized lithium would be an efficient source at 13.5 nm because the ratio of excitation energy to radiated energy is 53% and because only two electrons per atom need to be removed to produce that state.[9] The flux emitted at 13.5 nm by a lithium plasma within the bandwidth of multilayer optics was calculated to be optimized at an electron density of 10^{18}–10^{19} cm^{-3} and an electron temperature of 15–20 eV.[10] Low-inductance capillary discharges of compact design were shown to be capable of producing these plasma conditions while maintaining a small source size.[11] Thus it appears that a lithium plasma created in a capillary discharge may be a suitable source for EUVL and would be far more efficient and compact and significantly less costly than a LPP source.

Emission from the hydrogenlike lithium 3–2 transition at 78.9 nm radiated from plasmas excited in capillary discharges was previously characterized in studies of recombination x-ray lasers. In those investigations time-resolved lithium emission of lithium hydride (LiH) capillaries was reported in the wavelength region from 50 to 110 nm.[12] However, in no previous studies of which we are aware were measurements made of the spatial and output energy characteristics of these discharges at shorter wavelengths. The measurements taken at 13.5 nm that are reported herein show that the hydrogenlike lithium capillary discharge has significant potential for use as a compact and efficient 13.5-nm source of small spot size for EUVL.

Constructing and evaluating a lithium-vapor lamp to test our calculations would require developing a complex structure that must be compatible with the lithium vapor and operate at temperatures up to 900 °C. A simpler capillary discharge plasma device similar to the one described in Ref. 13 was therefore constructed to carry out the initial evaluations. LiH was used as the capillary material because it is electrically nonconducting and because it is a source of lithium atoms that easily become vaporized by the heat and radiation produced in the discharge. Furthermore, in the absence of contamination the only other species produced by the discharge is hydrogen, which has no transitions in the spectral region of interest and has only one possible ionization stage, thereby causing minimal loss of efficiency.

A 2-mm-diameter 6-mm-long LiH capillary was fabricated in a fashion similar to that described in Ref. 12. Forty-eight 3300-pF capacitors were arranged on a circular plate connected to the capillary, as shown in Fig. 1. The plate was charged to 15 kV, and a triggered spark gap initiated a discharge along the inner surface of the capillary so that the ablated material became heated, creating a highly ionized plasma. The geometry of the discharge circuit was chosen to minimize the inductance. The capillary was integrated into the spark gap to further lower the inductance, which was measured to be 84 nH. A calibrated Rogowski coil monitored the current pulse. The system was evacuated to a pressure of less than 10^{-4} Torr by a turbomolecular pump.

The radiation was viewed axially through a hollow electrode. It was analyzed with a flat-field spectrometer and an x-ray diode. The spectral data, which

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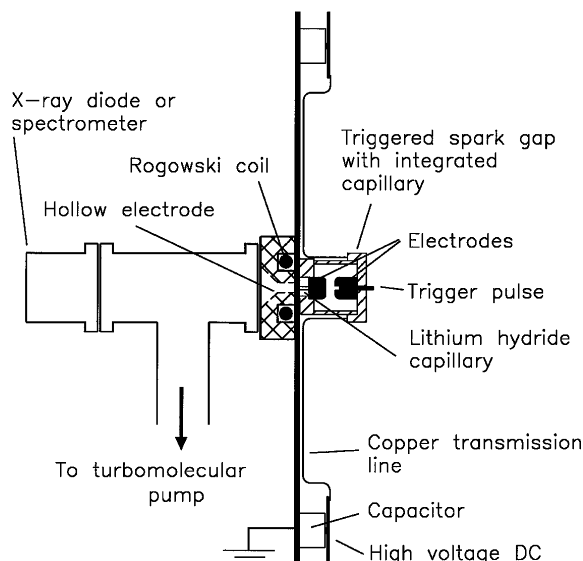

Fig. 1. Schematic diagram of the LiH capillary discharge setup.

were recorded on Kodak 101 film, were obtained with a spectrometer that covers a wavelength range of 5–20 nm, operating at a 3° angle of grazing incidence. It is based on a design described by Kita *et al.*,[14] which has a variably spaced grating with a nominal 1200 grooves/mm. The diode, which has an aluminum photocathode, detected radiation filtered by a 1-μm-thick beryllium (Be) foil. The Be filter transmissivity peaks at 11 nm (transmissivity ~30%) where the K edge occurs and decreases to ~2% at 20 nm, so the wavelength range in which the Be-filtered diode is sensitive lies entirely within the range of the grating.

Figure 2 shows the signal of the Rogowski coil and the x-ray diode recorded during the discharge pulse. A peak current of 25 kA and a FWHM of 250 ns were obtained. Nearly all the extreme-UV emission was observed to occur during the first half-cycle of the current pulse. Figure 3 shows the spectral emission over the bandwidth of the grating. In addition to emission lines from doubly ionized lithium, we also identified lines from five-times-ionized oxygen. LiH is hygroscopic, and because no special care was taken in handling the LiH the capillaries became contaminated with adsorbed water vapor during their construction. Thus we observed oxygen lines as well as lithium lines in the discharge spectrum.

To calculate the total flux over the wavelength range of 11–20 nm we integrated the diode signal weighted by both the diode responsivity and the Be filter transmissivity to determine the total number of photons detected by the diode. We then determined the relative contribution in the 11–20-nm bandwidth from each spectral line by direct measurement of the film grain density (Fig. 3) of each line weighted by the grating efficiency. We measured the total flux incident upon the diode, and, assuming that the capillary was a point source, we extrapolated 6 mJ/shot radiated into a hemisphere. The total conversion efficiency from electrical energy to energy radiated at 13.5 nm is nearly 0.05%. We estimate that half of the electrical energy is dissipated in the spark gap, so the effective conversion efficiency from energy deposited in LiH to 13.5-nm radiation is ~0.1%. It should be noted that this efficiency is obtained even in the presence of significant oxygen contamination.

We obtained soft-x-ray pinhole photographs of unity magnification, using a 100-μm pinhole 40 cm from the capillary, by inserting a 1-μm Be filter in front of the film plane. The images indicate that 75% of the energy was radiated from a spot size of 0.6 mm, corresponding to 4.5 mJ of energy emitted from a cylindrical volume of approximately 2 mm^3.

The radiation from this source was not optimized. The contamination of the LiH by water vapor resulted in undesired radiation from highly ionized oxygen.

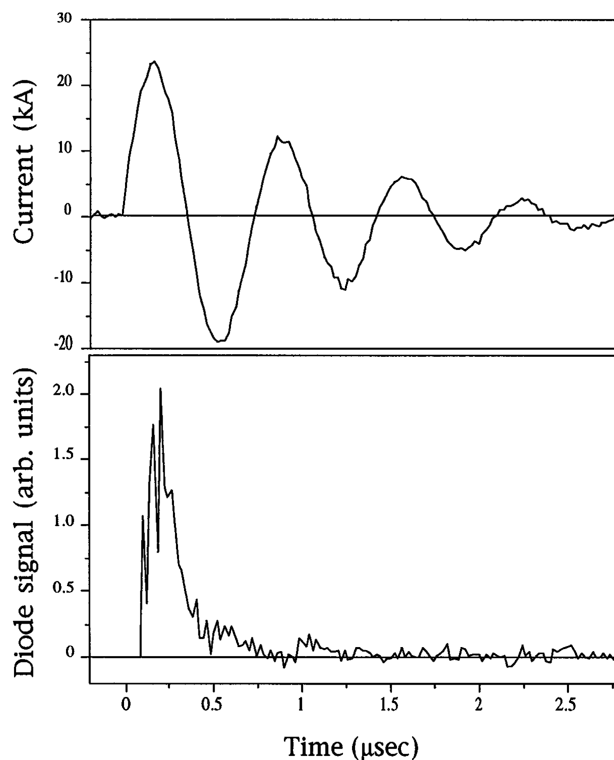

Fig. 2. Current pulse (top) and time-resolved soft-x-ray emission filtered by a 1-μm-thick Be foil (bottom).

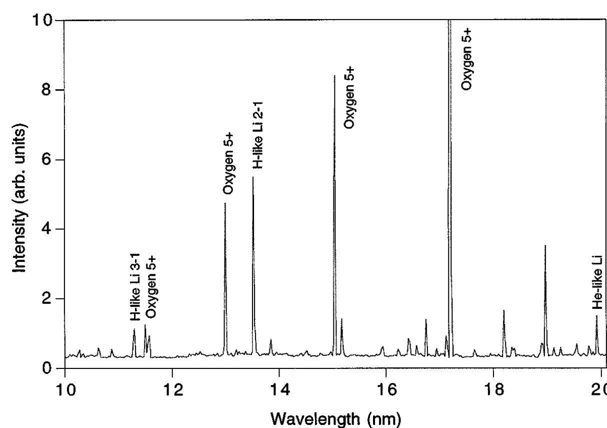

Fig. 3. Time-integrated axial emission soft-x-ray spectrum. Transitions from both lithium and oxygen are indicated.

One can significantly reduce this contamination by handling the LiH in either a dry-nitrogen or a noble-gas atmosphere. The presence of five-times-ionized oxygen indicated that an electron temperature of 20–30 eV was reached,[15] a temperature higher than the required 15–20 eV. It appears that more energy and efficiency could be obtained from the source if the LiH were not contaminated. In addition, shaping the current pulse such that the required electron temperature is attained would further increase the energy output. However, because this particular experiment was carried out only for the purpose of proof of principle, these optimizations were not subsequently implemented.

By examination of Fig. 3 it might be interpreted that oxygen could be an equal or better emitter in the extreme-UV spectral region, depending on the desired bandwidth. This, however, is an incorrect conclusion. For equivalent input energies we expect that a pure lithium plasma will be much more efficient than a pure oxygen plasma, especially within the desired wavelength range of 13–14 nm. There are four reasons for this: (1) Oxygen requires a higher plasma temperature than lithium to reach the ionization stage where strong extreme-UV emission can occur.[15] (2) The radiation from oxygen occurs in the fifth ionization stage, whereas in lithium it occurs in the second. Thus removing and heating the additional electrons from oxygen requires significantly more energy. (3) The energy required for populating the radiating state in lithium (from the neutral ground state) is 173 eV, whereas in oxygen it is 402 eV. (4) The lithium transition involves a resonance transition originating from the first excited state of Li^{2+} with a very high oscillator strength of 0.416, whereas each oxygen transition has a lower oscillator strength. The energy radiated from oxygen is divided among several transitions at a variety of wavelengths, as shown in Fig. 3.

The hydrogenlike lithium spectrum is narrow band (<0.1 nm) over the bandwidth of the Mo:Si multilayer mirrors. In contrast, most LPP sources being considered for EUVL use high-Z targets, and hence their emission is broadband. The emission outside the bandwidth of the mirrors not only is wasted but is also detrimental to the first collecting mirror in a lithography system because it is absorbed by the multilayer coatings, resulting in unwanted heating. In contrast, the lithium discharge source would cause almost no off-band heating. A lithium LPP was recently shown to be a highly efficient line radiator at 13.5 nm, but it is not a practical source for extreme-UV lithography because of significant debris problems.[10]

This experiment has successfully demonstrated that a LiH plasma is an effective source at 13.5 nm because it has produced a flux/pulse comparable with that of the most effective LPP (~6 mJ) within the bandwidth of a Mo:Si multilayer mirror. It is also compact and relatively inexpensive to construct and thus would be useful for single- or multiple-shot experiments such as those in extreme-UV microscopy. However, owing to its limited capillary lifetime (25–50 shots), it would require modifications to be useful as a source for high average power applications. Consequently a lithium source for EUVL will most likely consist of an oxygen-free high-temperature lithium-vapor discharge lamp.

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