Compact laser-plasma extreme-UV sources

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Very compact, debrisless, and efficient extreme-UV sources based on a gas-puff target enable nanometer-resolution imaging and development of a new technique for micro- and nanoprocessing of polymers.

The extreme-UV (EUV) regime extends from photon energies of approximately 25 to ~250 eV (corresponding to wavelengths from approximately 5 to 50 nm). Wavelengths in the nanometer range enable us to see smaller structures and write smaller lithographic patterns. In addition, the large number of atomic resonances in this spectral region provide mechanisms for both elemental and chemical identification. The EUV range is, therefore, highly attractive for various applications in materials science and nanotechnology. The best example is EUV lithography, the leading patterning technology for production of computer chips beyond the 193 nm node currently used for optical lithography. Other important applications, such as nanoprocessing materials using direct photo-etching, have recently also been proposed.

EUV radiation can be produced by synchrotrons. However, their limited number and very high associated costs imply that there is a strong need for development of a compact laboratory EUV source. EUV can be produced from a high-temperature plasma generated by the interaction of high-power laser pulses with matter. Various laser-plasma EUV sources have been proposed and considered for many applications in physics, materials science, biomedicine, and technology. Plasma is usually generated using laser-irradiated solid targets, but these have a serious debris problem. A large number of concepts to reduce debris production have been proposed, usually based on a mass-limited target approach. However, none has thus far solved the problem completely. We have proposed the use of a gas-puff target instead of a solid.1

Our target is produced by high-pressure, pulsed injection of a small amount of gas through a nozzle into the laser-focus region. We have demonstrated strong emission from this target under irradiation of nanosecond laser pulses. However, experiments studying EUV production have revealed several unacceptable features, most importantly nozzle degradation by the hot plasma and self-absorption of EUV radiation by the surrounding gas.2 To avoid these shortcomings, we have proposed a new concept based on a double-stream gas-puff target.3

This double-stream target is formed by pulsed injection of high-atomic-number (high-Z) gas into an additional hollow stream of low-Z gas using a double-nozzle setup (see Figure 1). The outer gas stream confines the inner stream, thus improving the target characteristics. This new approach enables production of targets with high gas density at larger distances from the nozzle output, which prevents nozzle degradation by the plasma. In addition, the plasma is surrounded by low-Z gas, which is transparent to EUV radiation. We have demonstrated strong enhancement of EUV production from our novel target compared to an ordinary gas-puff target created by injection of gas into a vacuum.4

Using this new approach, we have developed a compact laser-plasma EUV source for metrology applications (see Figure 2).5 We irradiate the target with 4 ns laser pulses and energies up to 0.8 J using a commercial 10 Hz neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (EKSPLA®). We successfully characterized molybdenum (Mo)/silicon (Si) multilayer mirrors6 and recently applied this source to nanometer-resolution imaging. We used a Fresnel zone plate with an

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outer-zone width of 50nm as objective. We obtained quasi-
monochromatic EUV radiation at 13.8nm (required for sample
illumination) by selecting a single line from the argon-plasma
spectrum produced using an argon gas-puff target. We applied
a Mo/Si ellipsoidal mirror of 80mm diameter and an incidence
angle of 45° as selector and obtained a spatial resolution (half-
pitch) of 69nm.7

The EUV source developed for polymer processing is
equipped with a grazing-incidence axisymmetric ellipsoidal
mirror to focus EUV radiation in the relatively broad spectral
range from approximately 5 to 50nm (with a strong maximum
near 10nm). The size of the focal spot was approximately 1.3mm
in diameter, with a maximum fluence of up to 70mJ/cm². We
performed experiments applying EUV irradiation to various
polymers and demonstrated efficient ablation and modification
of polymethyl methacrylate.8

Modification of polymer surfaces is primarily caused by direct
photo-etching with EUV photons and formation of micro- and
nanostructures onto the surface.9 The interaction mechanism
is similar to that of UV laser ablation, where energetic pho-
tons cause chemical bonds of the polymer chain to break.
However, because of the very low penetration depth of EUV
radiation, the interaction region is limited to a very thin sur-
face layer (<100nm). This makes it possible to avoid degrada-
tion of bulk material caused by deeply penetrating UV radiation.
The results of these studies should be applicable to biomedical
engineering.10 We recently developed a laboratory tool for
polymer processing that we will use for future studies on the
modification of polymer surfaces (see Figure 3).

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