A Source of Extreme Ultraviolet and Soft X-Ray Radiation Based on Z-Pinch Plasma

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Abstract – The paper presents the results of gas puff implosion experiments carried out on the IMRI-7 generator. The goal of the experiments was to verify the capability of a Z-pinch plasma radiation source to provide the radiation at the wavelength of 13.4 nm required for the EUV lithography applications. The maximum radiation yield at the wavelength of 13.4 nm was 55 mJ per pulse at the solid angle of 0.034 sr. The Z-pinch plasma radiation source meets the energy requirements of the EUV lithography applications, however further investigations are necessary for more detailed characterization of the radiation source and solving the problem of debris mitigation.

1. Introduction

Rapid development of microelectronics industry requires improvements in integrated circuit (IC) manufacturing. Further progress is related with subsequent miniaturization of the printable patterns to the size below 100 nm. The semiconductor industry is aimed at the critical dimensions of 30-70 nm to be adopted for mass fabrication. Extreme Ultra-Violet (EUV) lithography, which utilizes radiation in the range from 10 nm to 20 nm, is the most probable technology to be used.

At present, highly reflective multi-layer mirrors for the wavelength of 13.4 nm are available [1]. One of the most challenging problems in realization of EUV lithography remains a compact high power light source. EUV radiation can be provided by highly ionized atoms of high-temperature plasma. At present, several approaches are under development: laser produced plasma, gas discharges and vacuum spark [2]. This paper presents the results of experiments with a Z-pinch plasma radiation source intended for use in EUV lithography.

2. Experimental set-up

The IMRI-7 installation was designed for the experiments with a EUV radiation source. The generator works at the charge voltage of 6.5 kV. Capacitance of the storage capacitors is 7.5 μF, so the total energy stored by the installation is 150 J. Working at the short circuit regime, the generator provides the current of 100 kA with the current rise time of 400 ns.

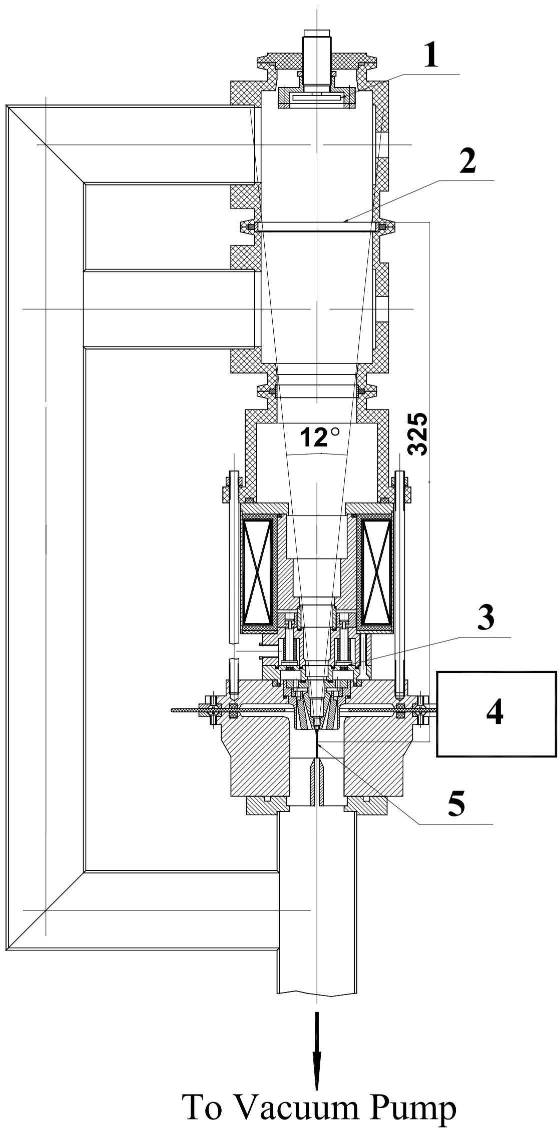

Fig. 1. Schematic drawing of the IMRI-7 installation: 1 – the x-ray vacuum diode; 2 – the protective filter; 3 – the gas valve; 4 – the capacitive energy storage with the triggered spark-gap; 5 – the Z-pinch implosion region.

The source of EUV radiation was Z-pinch plasma, which was formed as a result of the gas puff implosion. The gas puff was created in the interelectrode gap with the help of a fast electromagnetic gas valve. Design of the gas valve permitted formation of both single-shell and double-shell gas puffs. The EUV radiation was extracted from the top, along the Z-pinch axis. The advantage of such scheme is the absence of the working gas layer, which absorbs strongly the EUV radiation, between the source and a detector or a lithography optical system. Another benefit of this configuration is the minimal size of the EUV radiation source. The radiation was extracted into the solid angle of 0.034 sr. The schematic drawing of the IMRI-7 installation is shown in Fig. 1.

The measurements of EUV radiation were performed with the help of an x-ray vacuum diode (XRD). The XRD had a copper cathode and was placed behind a nitrocellulose (NC) filter with the thickness of 0.05-0.01 μm. The peak sensitivity of the detector was in the range from 10 nm to 30 nm.

3. Experimental results

The experiments were carried out with both single-shell and double-shell gas puffs. The single-shell gas puffs had the diameters of 9 mm and 16 mm. The double-shell gas puffs had diameters 23 mm (outer shell) and 9 mm (inner shell). Krypton and xenon were used as a working gases. For the given generators parameters, the estimated liner mass of the gas puff should be less than 1 μg/cm. There were doubts about normal operation of the gas puffs at such small linear masses. However, the experiments showed characteristic z-pinch implosions dynamics. Typical experimental oscillograms of voltage, current, and XRD signal, which registered the EUV radiation in the range from 2 nm to 30 nm, are shown in Fig. 2. It is necessary to note, however, that the given linear gas puff masses are close to a threshold for the gas puff Z-pinches. Even at the presence of strong preionization of the interelectrode gap, breakdown of the working gas occurs with a big delay.

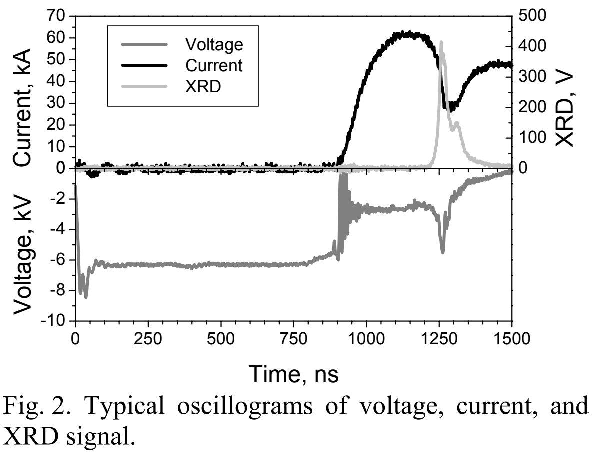

Fig. 2. Typical oscillograms of voltage, current, and XRD signal.

The maximum EUV radiation yield was registered in the experiments with xenon double-shell gas puffs that is equal to 55 mJ per pulse in the solid angle of 0.034 sr (conversion of the detector response was done assuming that the radiation flux in this solid angle is isotropic).

At present, we do not have the absolute measurements of the radiation yield at the wavelength of 13.4 nm. Based of the data of other researches [3], it is reasonable to assume that the radiation yield at the wavelength of 13.4 nm is 1-2% of the total radiation yield in the range of 10-30 nm. If it is assumed that all this energy is collected by the condenser optics and focused on a resist, then, taking into account reflectance of the multi-layer mirrors (the reflectance is about 70% at the wavelength of 13.4 nm), the energy on the resist with the area of 3 mm^2 is 1.5-3 mJ per pulse. The requirement for a lithography installation for the technology development and scientific research is that the radiation source should be able to illuminate a resist with the area of 1-3 mm^2 with the energy flux density of 5-6 mJ/cm^2. Thus, the IMRI-7 can provide the required energy in 2-4 pulses. In these estimations the transmission factor of a protective filter was not taken into account. Assuming the filter transmission factor in the range between 0.6 and 0.8, the required number of pulses should be increased to 2-8.

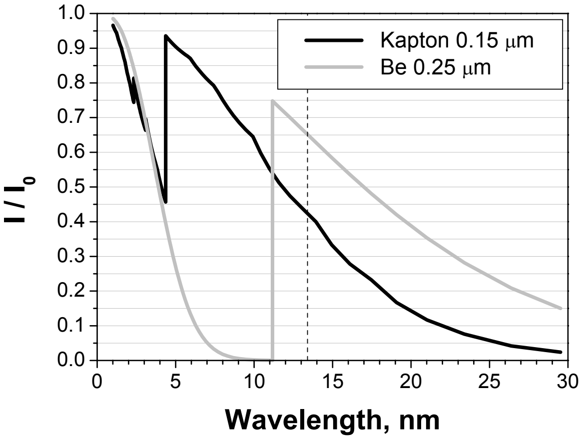

Fig. 3. Transmission factor of filters made of Kapton and beryllium.

A significant problem of using a Z-pinch radiation source for lithography application is the presence of debris from the plasma and electrodes. To provide a normal operation of the lithography installation, it is necessary to separate the volume of Z-pinch implosion from the projection unit. One of the possible ways employed in this research is the use of a protective filter. Besides the mechanical strength, such filter should have rather high transmission factor (60-80%) at the wavelength of 13.4 nm and radiation stability at comparatively small distance from the radiation source. An increase in the distance between a radiation source and the protective filter will require an increase in sizes of the condenser optics. There is a limited choice of the filter materials. The filter can be made of organic polymer films, which does not contain the elements heavier than oxygen, with the thickness up to 0.15 μm or beryllium foil with the thickness less than 0.25 μm. Transmission factors of such filters are shown in Fig. 3.

The most available material for the ultrafine filters is nitrocellulose. It is possible to made NC filters with the thickness up to 0.05 μm and the diameter up to 60 mm. If such filters will be able to withstand the debris, the filters from Mylar, polypropylene, Kapton and, especially, beryllium will provide reliable protection of the optical system of the lithography installation. The preliminary experiments on the IMRI-7 generator showed that the NC filters with the thickness of 0.05-0.1 μm and the diameter of 50 mm can withstand the debris impact at the distance of 325 mm from the Z-pinch region. However, the NC films have very low radiation stability, and they fail after 10-15 shots. It is highly possible that the films made of polypropylene or polyethylene will be more durable under the influence of EUV radiation, however production of the fine films with the thickness of 0.1-0.15 μm presents a significant technological challenge.

4. Summary

Preliminary experiments carried out on the IMRI-7 installation have shown that the Z-pinch plasma radiation source is capable of providing the radiation yield at the wavelength of 13.4 nm required for the EUV lithography applications. Further experiments are planned that will be aimed at more detailed investigation of the Z-pinch radiation source (source size, radiation spectrum, radiation flux distribution, etc.) and solving the problem of debris mitigation.

References

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