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Sources of ultraviolet light based on microwave discharges

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Today micro- and nano- electronics industry requires a source of extreme ultra-violet (EUV) radiation with a wavelength of 13.5 ± 1 % nm for high resolution projection lithography. The size of the emitting region must be less than 1 mm. One of the most promising sources of EUV light is considered to be a source that uses a pulsed CO_2 laser radiation focused on a specially formed stream of droplets of tin with dimensions of the order of 0.1 mm. However, along with tangible achievements in these light sources have a number of fundamental flaws that do not allow us to consider the problem of creating a EUV light source to be solved.

We propose a source of EUV radiation based on plasma heated by microwave radiation. The nonequilibrium ECR plasma is an effective source of radiation in the EUV region. Radiation of the plasma can lie in the region of 100 angstroms. This range contains the line radiation of multiply charged ions excited by electron impact.

The EUV line emission from a pulsed electron-cyclotron resonance discharge in argon, maintained by a high-power millimeter-wavelength beam in a magnetic mirror trap, was studied using a multilayer mirror EUV monochromator. The EUV spectrum was measured, and the absolute spectral intensity of emission was determined in a 6–17 nm wavelength range. The discharge can be used as an effective source of EUV light with an efficiency of the microwave to EUV light power conversion on a level of 10% and a maximum spectral power density of 7.3 kW/nm at a wavelength of 9 nm. Plasma was created and sustained by the microwave radiation with frequency of 37.5 GHz and power of about 100 kW. Scheme of the experiment shown in Fig. 1 [1].

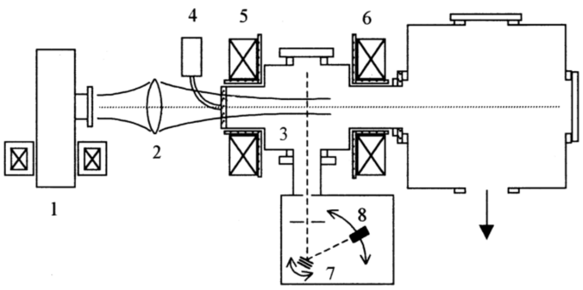

Fig. 1. Scheme of the experimental installation: (1) Gyrotron 130kW@37GHz, (2) lense, (3) plasma chamber, (4) valve, (5, 6) magnetic coils, (7) multilayer mirror, (8) EUV detector

Increase of the frequency of the heating radiation makes it possible to sustain plasma with higher density and propose the hybrid source of EUV light. Multiply charged ions are efficiently generated and excited in a discharge. Tin ions was injected into the magnetic trap from a vacuum-arc discharge and additionally stripped in the ECR plasma. Multicharged tin ions emit line radiation in the desired wavelength range. A radiation power of 50 W in a wavelength range of 13.5 nm ± 1% and an efficiency of about 1% for the conversion of the micro-wave radiation absorbed in the plasma to the extreme ultraviolet radiation were achieved in the experiments. Plasma was sustained by the microwave radiation with frequency of 75 GHz. Scheme of the experiment shown in Fig. 2 [2].

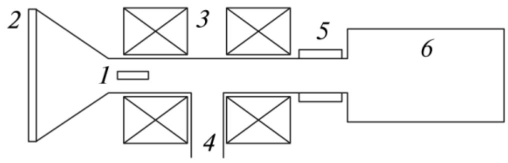

Fig. 2. Scheme of the experimental installation: (1) plasma generator, (2) microwave window, (3) magnetic coils, (4)pump-out channel, (5) magnetic cloak, (6) EUV detector or ion extractor and time-of-light analyzer of ion spectrum

A further increase in the heating radiation frequency and a transition to the terahertz range makes it possible to move close to the plasma parameters necessary to create a point-like source of extreme ultraviolet with the parameters necessary for high-resolution lithography. An increase in plasma density with increasing frequency of the heating wave to the value of 10^{15} cm^{-3} and above makes a plasma resonance heating mechanism effective with small plasma size [3]. The main idea of creating of a point-like discharge with high emissivity in the required wavelength band is the realization of a breakdown in a nonuniform gas jet with the scale of the inhomogeneity of the order of 1 mm. In this case, breakdown conditions fulfilled only in a small region of space and discharge cannot go beyond it [4]. The scheme of the experiment is presented on Fig. 3. Typical photo of the discharge is presented on Fig. 4.

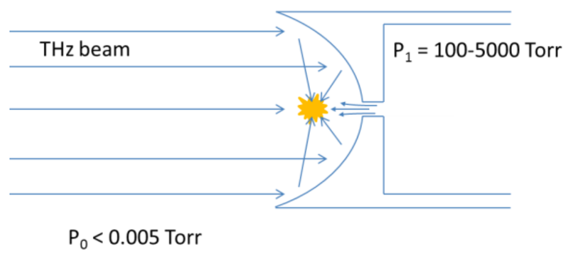

Fig. 3. Scheme of the experiment

THz radiation was coupled into the discharge vacuum chamber and focused by a parabolic mirror; THz wave power density reached 40 MW/cm^2, ensuring stable gas breakdown for the pressure values of about 20 Torr. A small nozzle (80 μm in diameter) connected to a buffer volume was incorporated in the mirror for inhomogeneous gas flow production. Neutral gas flow was ∼10^{20} particles/s at a gas pressure of 2–3 bar in buffer volume, which corresponds to ∼1 bar pressure at the nozzle outlet.

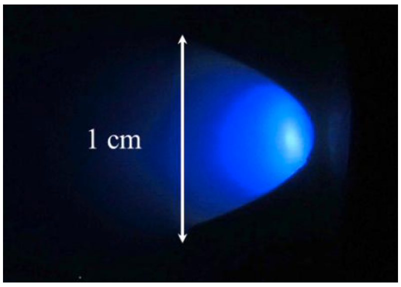

Fig. 4. Photo (in visible light) of the point-like discharge. Argon. Radiation frequency of 670 GHz

The electron concentration was determined using Stark-effect induced broadening of the H_α atomic emission line (656.3 nm) of hydrogen present in discharge as a small impurity in residual gas. The maximum observed Stark broadening of the H_α line corresponded to a plasma density on the order of 2×10^{16} cm^{-3} (see Fig. 5) which exceeded the critical value for the given frequency (670 GHz) of radiation sustaining the discharge [5].

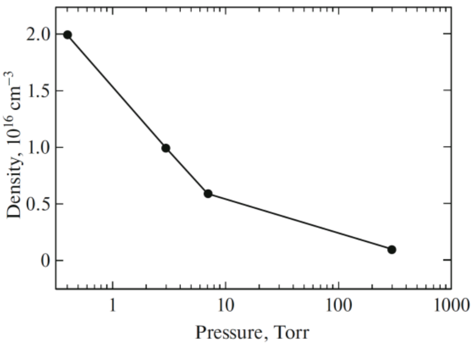

Fig. 5. Plasma density vs. background argon pressure in the discharge chamber

Output EUV radiation was measured using both photomultiplier with operating range from 112 to 400 nm and photodiode covered with different filters. Both measuring devices were connected to oscilloscope. For our experiment we used a single Mo/Zr filter with a transmission of 45 % near 13.5 nm wavelength range and almost zero in the rest range (see Fig. 6).

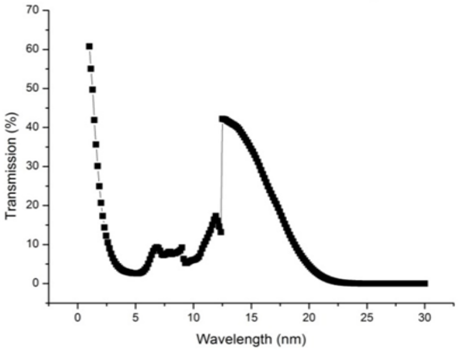

Fig. 6. Transmission spectrum of the Mo/Zr filter

Photo of a point-like xenon discharge in optimal for EUV light conversion conditions is shown in Fig. 7. In this case there is an area inside the plasma witch is slightly darker than the rest plasma's sphere. That can be caused of the fact that temperature in the center of the discharge is high enough to generate EUV photons, so plasma starts to be invisible for the camera.

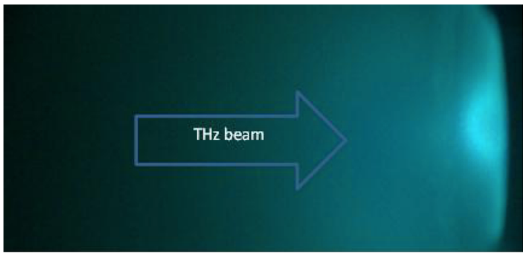

Fig. 7. Photo (in visible light) of the point-like discharge in the optimal conditions. Xenon. Radiation frequency of 670 GHz

Measured in the optimal conditions EUV radiation of the point-like discharge in the wavelength range 12 - 17 nm was of 100 W/cm^3. Conversion efficiency from THz radiation to EUV emission can be raised by increasing duration and power of the heating pulse.

Acknowledgements

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