A POINT-LIKE SOURCE OF EXTREME ULTRAVIOLET RADIATION BASED ON NON-EQUILIBRIUM DISCHARGE, SUSTAINED BY POWERFUL RADIATION OF TERAHERTZ GYROTRON*

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Abstract

It is proposed in this paper to use discharge plasma supported by terahertz radiation as a source of EUV light for high-resolution lithography. In this report we discuss the experimental investigation of two types of EUV sources based on discharge, supported by powerful gyrotron radiation. Following investigation results are described:

-a series of experiments that demonstrate the generation of EUV light from the vacuum-arc discharge plasma in tin vapor in the magnetic trap heated by gyrotron radiation with a frequency of 75 GHz under electron cyclotron resonance (ECR) conditions;

-a numerical modelling of the plasma emissivity in the EUV range, depending on the parameters of the heating radiation is performed;

-experimental studies of EUV emission from plasma discharge sustained by strong terahertz powerful radiation in inhomogeneous gas flows are started.

INTRODUCTION

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 power of the source must be at a level of 1 kW at the size of the emitting region of less than 1 mm.

One of the most promising sources of EUV light is considered to be a source that uses a pulsed CO2 laser radiation focused on a specially formed stream of drop-lets of tin with dimensions of the order of 0.1 mm [1]. 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 to use discharge plasma supported by terahertz radiation as a source of EUV light for high-resolution lithography. In this report we discuss the experimental investigation of two types of EUV sources based on discharge, supported by powerful gyrotron radiation. Following investigation results are described:

- a series of experiments that demonstrate the generation of EUV light from the vacuum-arc discharge plasma in tin vapor in the magnetic trap heated by gyrotron radiation with a frequency of 75 GHz under electron cyclotron resonance (ECR) conditions;
- a numerical modelling of the plasma emissivity in the EUV range, depending on the parameters of the heating radiation is performed;
- experimental studies of EUV emission from plasma discharge sustained by strong terahertz powerful radiation in inhomogeneous gas flows are started.

ELECTRON CYCLOTRON RESONANCE HEATING EXPERIMENTS

The experimental scheme is following: tin ions injected into the magnetic trap from a vacuum-arc dis-charge. Low-pressure discharge sustained in a magnetic trap by the high-power millimetre-wave radiation (200 kW @ 75 GHz) under ECR conditions. Multiply charged ions are efficiently generated and excited in such a discharge and emit line radiation in the desired wave-length range [2]. Experimental layout is in the Fig. 1.

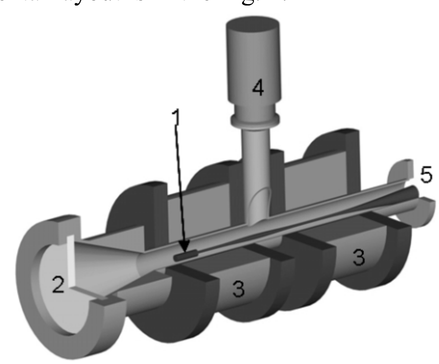

Figure 1: Experimental setup 3d-scheme. 1 – plasma generator, 2–window for microwaves, 3 - coils, 4 – EUV detector, 5 – flange for plasma analysis or EUV detector.

The charge state distribution of tin ions achieved in these experiments is shown in Fig. 2. 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.

NUMERICAL SIMULATION

The efficiency of the source of the EUV radiation was estimated as follows. The system of the rate equations for the densities of the charged particles in various ionization states was solved. The initial mean charge of the tin ions in the injected beam was 2. The microwave-radiation

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ISBN 978-3-95450-158-8

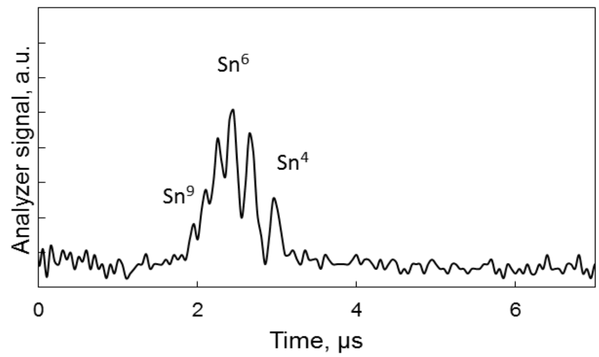

Figure 2:Tin-ion distribution over the degree of ionization in the vacuum-arc plasma heated by microwaves.

power necessary to sustain plasma with a certain electron temperature T_e (the power absorbed by the plasma) was calculated as the sum of the energy carried out from the trap mirrors by the plasma and the energy spent for the ionization and excitation of the ions followed by emission. The radiative losses from the plasma were calculated as follows. Density of the plasma and the resulting ion distribution over charges were calculated for a given flow of plasma in a trap (defined by vacuum arc current I_{arc}) and a fixed T_e. Then EUV light power was estimated using the averaged constants for the excitation rate of multiply charged tin ions [3]. The most impressive results are plotted in Fig. 3.

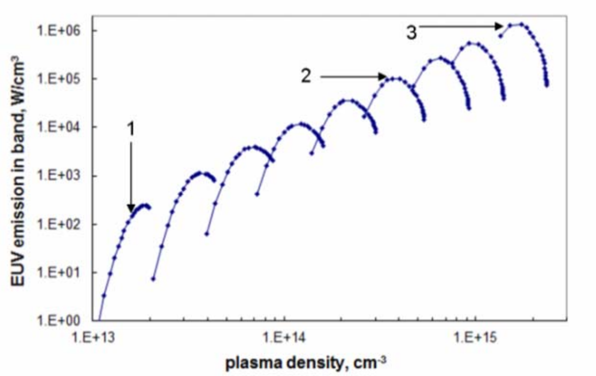

Figure 3: Radiation power calculations in the range of 13.5 nm ±1% into a solid angle of 4 π sr for the predetermined Te and Iarc. Resulting points calculated for fixed I_{arc} and different T_e are connected by lines.

Arrow 1 shows the calculation for the parameters of the experiment described above. Performance of the EUV light source could be improved by increasing the plasma density. For example, the use of plasma heating waves with frequency of 170 GHz will make it possible to reach plasma density values up to $4{\cdot}10^{14}$ cm^{-3}. And the longitudinal size of the emitting region will be less than 5 mm. This example marked with arrow 2 in Fig. 3. To reach desired 1 kW of light power in desired band and size of the source less than 1 mm further increase of the frequency of the heating radiation is needed. 300 GHz will make it possible to reach plasma density values up to 10^{15} cm^{-3}. And the longitudinal size of the emitting region will be about 1 mm. In this case conversion efficiency and total EUV light emission could be 5 % and 1 kW. This example is marked by the arrow 3 in Fig. 3.

TERAHERTZ WAVE HEATING EXPERIMENT

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 [4, 5]. This removes the need to use high magnetic fields. The main idea of creating of a point discharge with high emissivity in the required wavelength band is the realization of a breakdown in a non-uniform 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. General view of the experimental setup (without gyrotron) is shown in Fig.4. The plasma was ignited by gyrotron radiation with a frequency of 0.67 THz and power up to 200 kW in pulses lasting from 20 to 50 µs [6].

Figure 4: Photo of the experimental setup. 1 - discharge vacuum chamber, 2 – manipulator with the gas inlet and an additional focusing mirror, 3 - vacuum pump, 4 – microwave beam mode converter, 5 - additional focusing parabolic mirror with a nozzle to form a non-uniform flow of gas.

Gyrotron radiation transformed into Gaussian beam by quasi-optical converter was directed into the discharge vacuum chamber, where was additionally focused by a parabolic mirror (5), maximum value of the THz wave power density was of about 40 MW/cm^2 that ensured stable gas breakdown for the pressure values of about 20 Torr. A small nozzle (150 µm in diameter) connected to a buffer volume was drilled in the centre of the mirror (5) for producing an inhomogeneous gas flow. Neutral gas flow was about 10^{20} particles/sec at a gas pressure of 2-3 atm in buffer volume, which corresponds to approximately atmospheric pressure at the nozzle outlet. The pumping system allowed to maintain background pressure on the level of 10^{-2} – 10^{-3} Torr. Argon was used as a gas in the first experiments (expedience of using xenon gas in real sources is obvious). In spite of the lack of emission lines into the required band for the projection lithography this gas seems optimal for the demonstration of principal opportunity to use terahertz gas discharge as

ISBN 978-3-95450-158-8

an effective point-like UV source. Terahertz wave beam power and gas inlet parameters were chosen to fulfil breakdown conditions near the focus of the parabolic mirror and ignite the discharge. Discharge glow diagnostics was performed using a several photomultipliers ("Photon-1" in the wavelength range of 200 - 650 nm and PMT-142 with the MgF_2 window and removable quartz filter in the vacuum ultraviolet range – 112-400 nm). The boarder of the quartz filter free pass was close to the wavelength of 180 nm.

The main purpose of this work is to study the possibility of obtaining a point-like discharge plasma with size less than 1 mm and parameters (T_e, $N_e\tau$) providing VUV radiation by using a non-uniform gas flow. It is necessary to provide the breakdown conditions near and only near the nozzle to localize the discharge (gas pressure in this area should be about atmospheric pressure which corresponds to the minimum of the breakdown curve for quasi-optical beam of terahertz radiation [5]), which requires steep gas pressure gradient, that is, effective pumping. To illustrate the Figure 5 shows photographs of the discharge for different values of background gas pressure in the vacuum chamber.

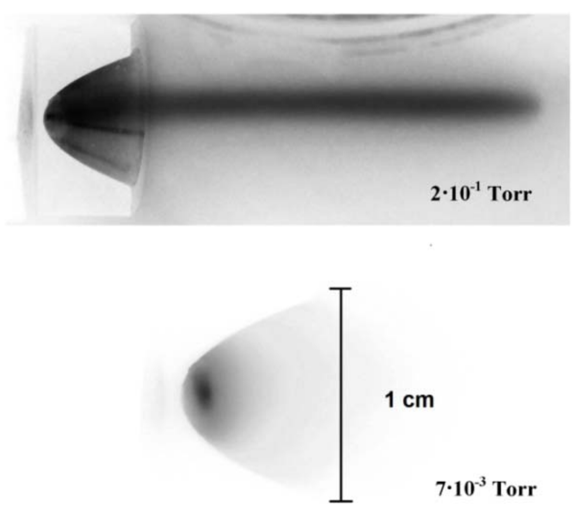

Figure 5: Discharge glow photographs at the values of the background gas pressure $2\cdot10^{-1}$ Torr (upper) and $7\cdot10^{-3}$ Torr (lower).

It is clearly seen that at relatively high background pressures (10^{-1} Torr) discharge emerged at the high-pressure region near the nozzle extends towards radiation and ends in the area where the breakdown conditions are not fulfilled. The same could be seen from the Figure 6 showing the discharge optical scan obtained by a streak camera FER-27. Discharge existence in the region with initial field intensity less than the breakdown value apparently could be realized due to the electric field normal component amplification in inhomogeneous plasma at the plasma resonance point [7].

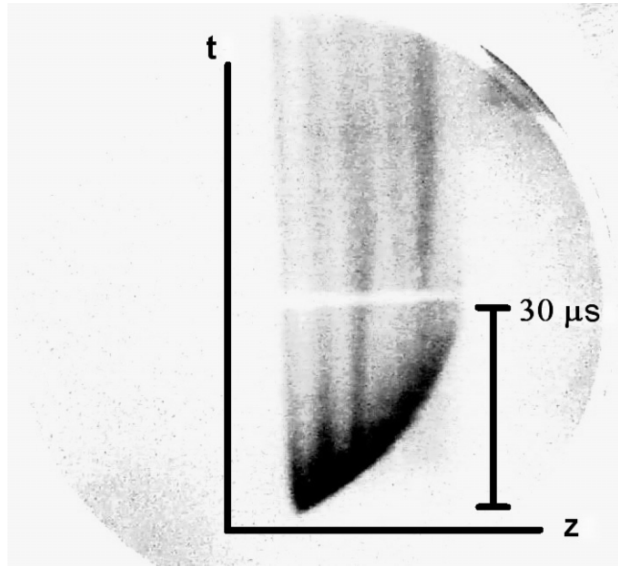

Figure 6: Streak camera FER- 27 scan-image of the discharge glow. Vertical axis represents time, horizontal axis is the coordinate directed to the electromagnetic radiation source.

With the background gas pressure decrease discharge reduced its dimensions and at the pressure less than $5\cdot10^{-2}$ Torr it became localized near the nozzle. Light emission of such point-like discharge was studied in the wavelength range from 650 nm to VUV region. Figure 6 shows the waveforms of photomultiplier signals obtained at background pressure of $3\cdot10^{-2}$ Torr.

Time evolution of the discharge glow comes into notice: it is clearly seen that the intensity of the discharge glow in the VUV range increased right after the end of the THz radiation pulse and the glow in the visible range increased only after hundreds of microseconds together with the decay of the VUV emission. This behaviour can apparently be explained as follows. During the terahertz radiation pulse when electron temperature is relatively high formation and excitation of multiply charged ions by electron impact takes place together with subsequent de-excitation in the VUV band. After the pulse end electron temperature decreases which leads to sharp increase of the rate of radiative recombination in three-body collisions (it is proportional to $T_e^{-9/2}$) and rapid increase of recombination radiation intensity. Then, the plasma ionization degree decreases down to the level where only low-charged ions remain, plasma recombination luminescence spectrum shifts from the VUV to the visible range (Fig . 7). We assume that the excitation of multiply charged ions by electron impact during the THz radiation pulse is changed to their excitation by impact-radiation recombination. It should be noted that radiation intensity in the optical band increase with the gas pressure in opposite with the radiation intensity behaviour in the VUV region: for the pressure values of about 10^{-1} Torr discharge hardly radiated in the VUV band. This fact could be noticed after the comparison of the PMT-142 signals with and without quartz filter (for relatively low

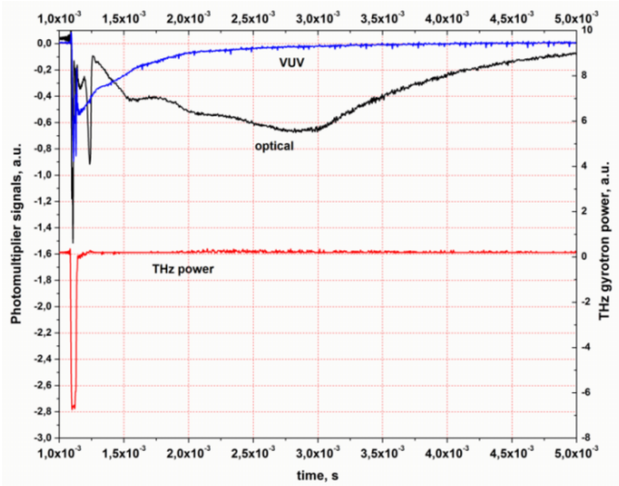

Figure 7: Signals from photomultipliers in optical and VUV regions (upper). Lower signal – THz radiation power pulse. Background gas pressure $3{\cdot}10^{-2}$ Torr.

pressures signal without filter was in several times more, for high pressures they were close). The value of the VUV radiation power can be estimated from the low bound using a data of PMT-142 sensitivity. Comparison of the PMT-142 signals at low pressures with quartz filter (that cut off the radiation with the wavelength low than 180 nm) and without it demonstrated that in assumption of the isotropic radiation 10 kW of radiation total power fell on the range of 112-180 nm.

These results demonstrate the feasibility and prospects of EUV point-like source creation on the basis of a discharge in a non-uniform gas flow sustained by a powerful terahertz radiation. It should be noted that the first experiments were carried out using cheap and available noble gas Argon. Argon does not have as many emission lines in the desired wavelength range as Xenon does (it was shown that xenon discharge emission efficiency in the range of 13.5nm ± 1% could be up to 1%, and in the range of 11.2 nm ± 1% up to 4 % of energy absorbed by the plasma [8]). THz gyrotron with 50 kW CW power at 1 THz should be enough to create 13.5 or 11.2 nm EUV source of such type with output power at the level of 0.5 kW assuming the reasonable level of terahertz radiation absorption efficiency (dozens of percent as it was mentioned above). Last developments in gyrotron technologies offer possibility of such generators production [9].

ACKNOWLEDGMENT

The work was supported by RSF within grant No 14-12-00609.

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