Discharge produced plasma source for EUV lithography

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ABSTRACT

Extreme ultraviolet (EUV) radiation is seen as the most promising candidate for the next generation of lithography and semiconductor chip manufacturing for the 32 nm node and below. The paper describes experimental results obtained with discharge produced plasma (DPP) sources based on pinch effect in a Xe and Sn vapour as potential tool for the EUV lithography. Problems of DPP source development are discussed.

Key words: EUV source, lithography, discharge produced plasma, rotating disk electrode, excimer laser.

1. INTRODUCTION

Next generation High Volume Manufacturing (HVM) of semiconductor chips using extreme ultraviolet lithography (EUVL) to achieve critical dimensions <32 nm requires a brilliant radiation source with unique parameters. The wavelength of the source emission was chosen to be 13.5 nm since current approaches to the optical system are designed to use this illumination wavelength because a high reflectivity (≈66%) of multilayered MoSi mirrors is achieved at 13.5 nm.

To develop HVM EUV lithography the main lithographic tool manufacturers (ASML, Canon, Nikon) require to deliver 115-180 W (13.5 nm, BW=2%) in intermediate focus at the entrance of the exposure tool[1]. Taking into account the condition of transportation of EUV radiation to the intermediate focus (Fig.1) the EUV power of the source must be more than 1000 W (13.5 nm, BW=2% in 2π sr). The source parameters supporting specifications[1] required for EUV lithography are summarized in the table.

Central wavelength	13.5 nm
EUV output power in 2π sr (BW=2%)	>1 kW
Input power	~200 kW if CE=0.5% or 50 kW if CE=2%
Maximum atendue of source output (square×solid angle)	1- 3.3 mm^2 sr
Pulse to pulse stability	< 5%
Electrode lifetime	> 10^{11} pulses

A conversion efficiency (CE) is calculated as ratio of the EUV power (13.5 nm, BW=2% in solid angle 2π sr) to the input electrical power in the discharge.

The achievement of such high EUV power level in combination with long lifetime (~10^{11} pulses) of both source and optics makes the source to one of the most critical issues in the development of EUV lithography. EUV source development is based on the use of hot plasma capable of efficiently emitting around 13.5 nm. Such a plasma can be produced either at the focal spot of a laser beam or in a discharge. In the latter case a direct conversion of the electrical energy, stored in a capacitor bank, into the energy of emitting plasma can increase the source efficiency and simplify its technology. To ensure an efficient emission in the spectral range around 13.5 nm the electron temperature of both laser and discharge plasmas should be in the range 20-30 eV.

2. EUV SOURCE BASED ON XENON Z-PINCH

A schematic drawing of Xenon Z-pinch EUV source developed at SRC RF TRINITI is shown in Fig.1. Hot Xenon plasma was produced by using preionization from a surface discharge on a cylindrical dielectric. The preionization ensures the

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ignition of a discharge in the main discharge gap, improves the pulse-to-pulse stability of EUV energy, and increases the efficiency of EUV emission from the plasma at the final stage of the pinch discharge. A cylindrical plasma shell created in the course of the preionization contracts to a hot dense plasma column on the axis of the discharge gap under the action of the pulsed magnetic field pressure produced by the main discharge current with an amplitude of several tens of kiloamperes. To ignite a high-current Xenon Z-pinch discharge we used a two-stage pulsed magnetic compression circuit with a stored energy ranged between 8 and 20 J/pulse. To ensure the source operation at high (≥10 kW) input power the elements of discharge chamber were intensively cooled with water. Collector angle was 1.8 sr.

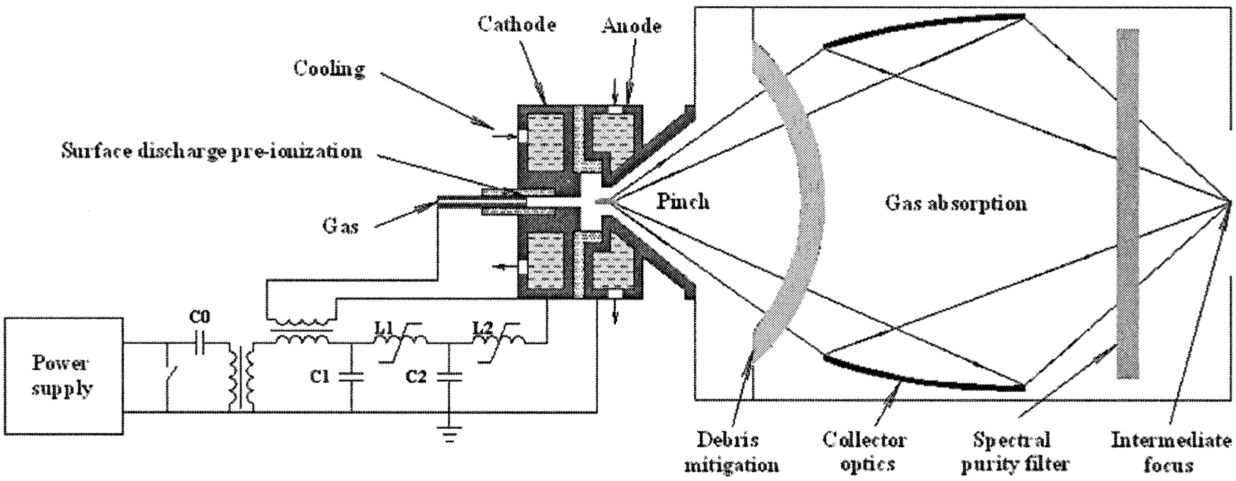


Fig.1. Schematic of both Xenon Z-pinch EUV source and collector module.

The size of EUV emitting plasma region was determined 0.25 mm (FWHM) in diameter and 1.5 mm (FWHM) in length.

For the DPP sources using Xe the maximum of the EUV power was of about 250 W (BW=2%) in 2π sr. This EUV power was obtained just near the plasma pinch region. As the Xe gas absorbs the EUV radiation outside the discharge region the measured EUV power depends on both the distance from the plasma pinch to the measuring tool and residual Xe pressure which, in turn, depends on the pump speed.

With Xenon source the EUV power of about 90 W (BW=2%) in 2π sr was measured for the distance between the plasma pinch and the measuring tool of 1.2 m for continuous operation at a repetition frequency 2000 Hz. The conversion efficiency CE is calculated as 0.45% [2].

Photo of Xenon Z-pinch EUV source developed at SRC RF TRINITI is shown in Fig.2.

Using the results with the Xe source obtained at SRC RF TRINITI our partner XTREME technologies (Germany) has started to ship first commercial prototypes of EUV sources to customers. Among others two of these sources have been integrated into EUV micro exposure tools at Exitech. Then micro exposure tools were installed in the laboratories of Intel and International Sematech, both USA[3].

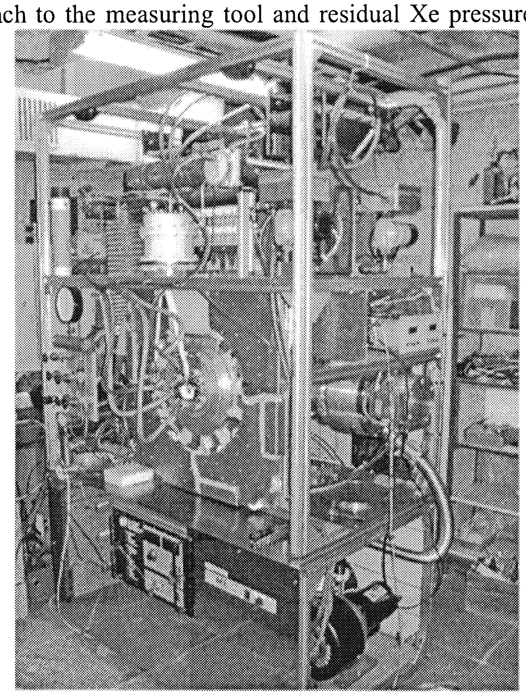


Fig.2. Photo of Xenon Z-pinch EUV source developed at SRC RF TRINITI.

Our experiments have shown also that the lifetime of the source depends on the configuration, materials of both electrodes and insulator, on the method of cooling, on the level of electrical power dissipated in the discharge and on the parameters of the pulsed discharge (voltage, current, pulse duration). In the electrode configuration shown in Fig.1 both the anode and the cathode were fabricated from copper with tungsten inserts. The electrodes were separately cooled by water at a total flow rate of up to 5 liters / minute. We studied the electrode mass loss for different conditions during continuous operation of the EUV source. The erosion for both the cathode and the anode measured after the run tests at different levels of input power is shown in Fig.3. The anode erosion was higher the cathode one. As seen from Fig.3, the increase of input power from 5 to 20 kW does not result in an increase of the erosion. This result contradicts a common opinion that an increase of input power should result in a nonlinear growth of erosion. Probably, it is possible to explain by a phenomenon known as "vapor shielding". Essence of the phenomenon is that under the action of high-power plasma fluxes the wall starts to evaporate intensively. The vapors of the wall material being ionized by the radiation of plasma pinch form a plasma wall layer, protecting the wall surface against the plasma fluxes.

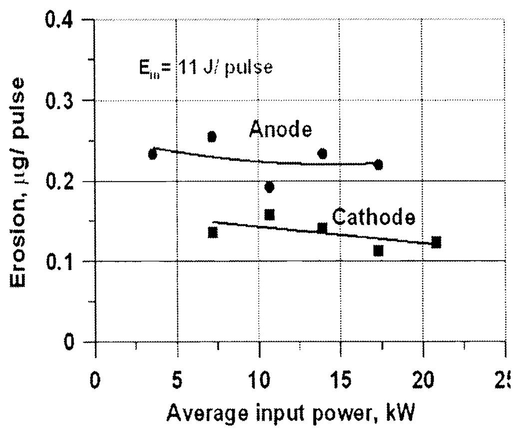


Fig.3. Electrode erosion as a function of input power.

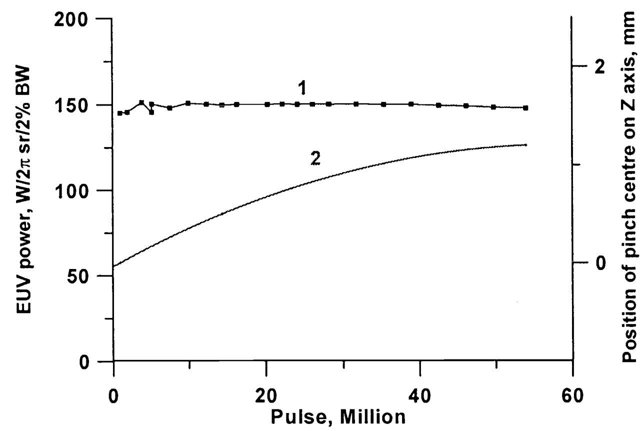


Fig.4. EUV power just near of plasma (1) and displacement of Z-pinch center of gravity (2) during continuous operation at 1.1 kHz.

Electrode erosion (~0.1 μg/pulse for the cathode and ~0.2 μg/pulse for the anode) does not allow achieving the long electrode lifetime required for EUV source which could be used for HVM lithography. As seen from Fig.4, under operation with EUV output power near of plasma ~ 150 W/ 2π sr / 2% BW the significant (~ 1mm) displacement of the pinch center of gravity along Z-axis was observed after 50 million pulses. This displacement of pinch position toward the cathode is the result of change of the cathode geometry caused by electrode erosion under continuous operation with input power around 12.5 kW.

Taking into consideration that required EUV power level is about 1 kW and CE≈0.5%, the input power must be as high as 200 kW! So EUV source concept based on Xe as a plasma fuel would not be able to meet the HVM requirements.

The solution for the development of HVM EUV source is an increase of CE and a reduction of a heat power load on the electrode surfaces.

The potential solution can be realized by the following concept of the EUV source.

3. EUV SOURSE WITH ROTATING DISK ELECTRODES (RDE) BASED ON TIN AS PLASMA FUEL

It is known that Sn ions have a very intensive spectral peak around 13.5 nm. In contrast to Xe this Sn peak is formed by emission of many excited states of ions from Sn^{+7} to Sn^{+12} and one can expect that in such DPP sources using Sn the CE can be much greater than using Xe. The concept of the EUV source is based on a laser triggered vacuum arc between rotating disk electrodes (RDE) covered with a constantly regenerated Sn layer. In principle, there are different versions to realize the concept of the EUV source using the RDE configuration with Sn as plasma fuel.

3.1. Version of the RDE source using solid tin cathode

Figure 5 shows the schematic diagram of the RDE source used in experiments. The metal disk anode was separated from the metal disk cathode by an insulator. The anode and the cathode were rotated together by an electrical motor. The pulsed power system connected to the electrode disks by the sliding contacts provided the energy dissipated in the discharge ranging from 2 to 5 J/ pulse. The edge of the rotating disk cathode was covered with a tin layer. The rotating disk electrode system was placed in a vacuum chamber. This chamber had window for the input of laser beam and nipples for mounting of the pinhole camera and the EUV power meter.

The electrical energy was delivered to the plasma after producing tin vapour by a pulsed laser beam focused on the cathode disk edge covered with the tin layer. In our experiments excimer laser could provide pulse energy up to 90 mJ at λ=248 nm and up to 40 mJ at λ=353 nm with repetition frequency up to 4000 Hz. It is necessary to emphasize that the laser radiation initiated the both appearance of tin vapours and vacuum gap breakdown only. The main energy dissipated in the discharge occurred due to electrical energy stored in the capacitor battery. Nevertheless, our experimental results showed that laser parameters could significantly influence output parameters of the EUV source.

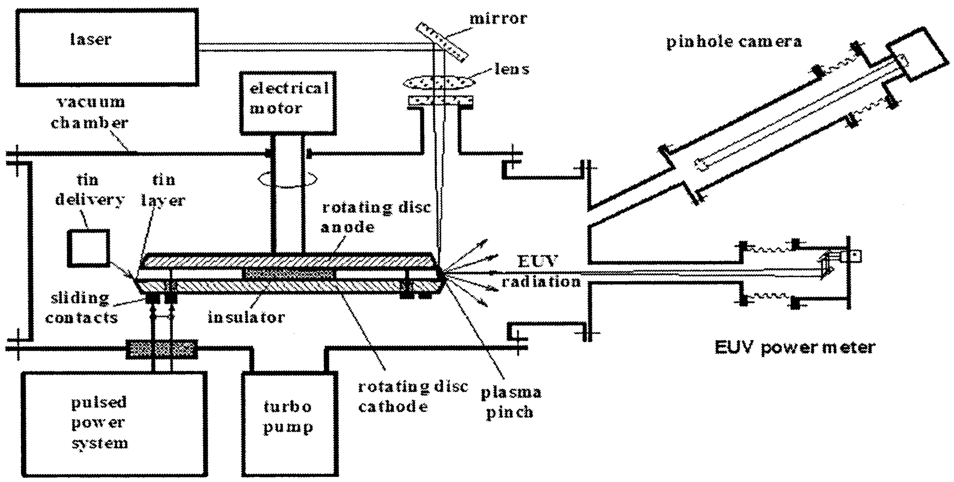


Fig.5. Schematic diagram of experimental RDE EUV source.

In the case when the cathode was covered with solid tin, the measurements with the pinhole camera showed that region of EUV emitting plasma was located mainly near the cathode, Fig.6. This region had diameter 0.3 mm (FWHM) and length 0.5 mm (FWI

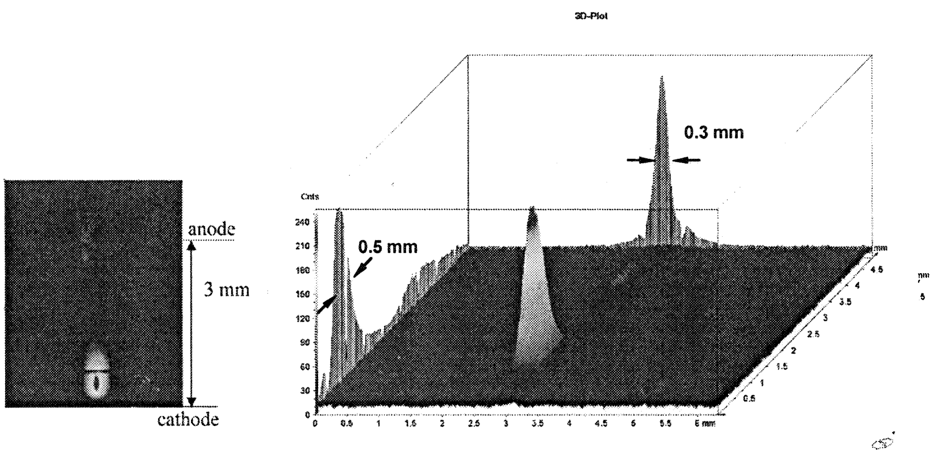


Fig.6. EUV radiation of the discharge between the cold cathode covered with tin and copper anode.

When the electrode disks were not rotated and the laser beam was focused in the same point of the tin surface on the cathode, the tin layer remained solid to next pulse at low repetition rate (< 10 Hz). The evolution of EUV energy registered under these experimental conditions is shown in Fig.7a. Simultaneous measurement with pinhole camera (Fig.7b) has shown that the image of the EUV emitting region changed from pulse-to-pulse and EUV- light intensity decreased during about 400 pulses. After 400 pulses we have noticed a crater in tin surface of the cathode where the vacuum arc was localized.

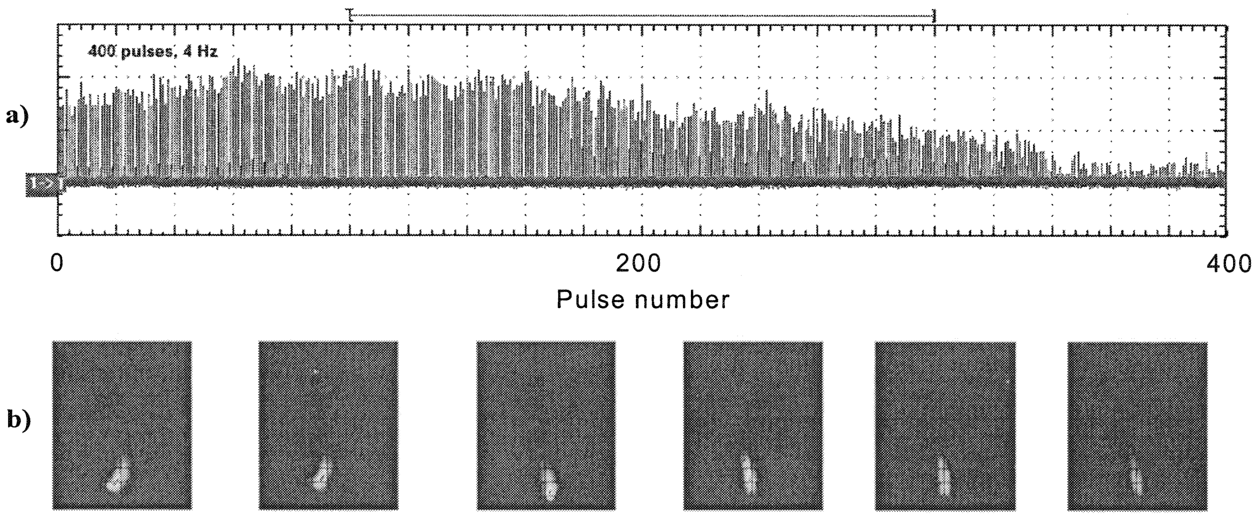


Fig.7. Sequences of EUV radiation signals (a) and EUV images (b) of the discharge between non-rotating cathode, covered with tin, and copper anode.

In order to understand the reason of EUV energy degradation we carried out additional measurements with gridded ion detector tuned for measuring the ion current in plasma ejected from laser focus spot on cathode surface covered with tin. The ion detector was placed in one of measuring nipples of EUV source setup shown in Fig.5. After every fifty discharge pulses we measured ion current produced by laser pulse only (at absence of the discharge).

Figure 8 demonstrates the decrease of ion current with number of discharge pulses. It means that quantity of tin plasma produced by focused laser beam decreases with the number of discharge pulses, evidently due to growing of crater on the cathode surface. In turn, this phenomena leads to the decrease of EUV light emission with number of discharge pulses, shown in fig.7 for a case of non-rotating cathode.

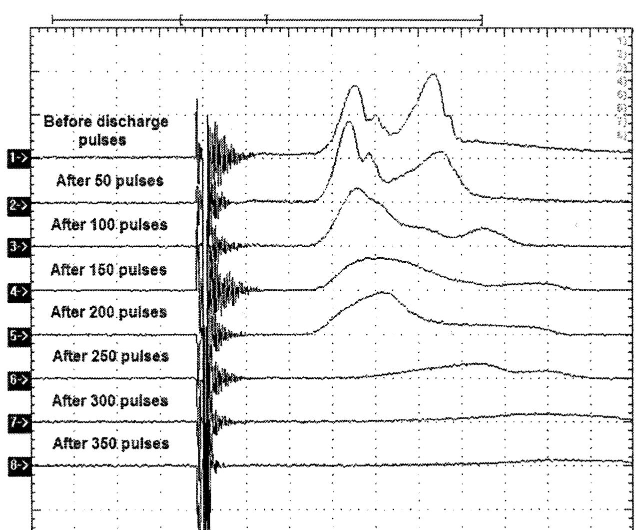


Fig.8. Measured ion current in plasma ejected from laser focus spot on cathode surface covered with tin.

When the electrode disks were rotated with a speed 1-3 revolutions per second the mean EUV pulse energy and pulse-to-pulse stability decreased, fig.9.

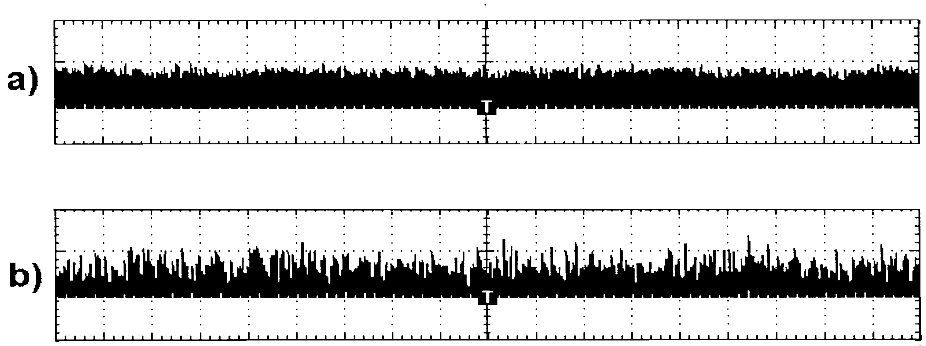


Fig.9. Sequences of EUV signals after 30 sec (a) and after 30 min (b) of start of source operation with pulse repetition rate 1 kHz at input power ~ 6 kW.

The reason of EUV light degradation and an increase of pulse-to-pulse instability is a formation of a tract on the tin cathode surface (Fig.10) and as consequence of this phenomenon a decrease of the tin plasma, ejected from cathode.

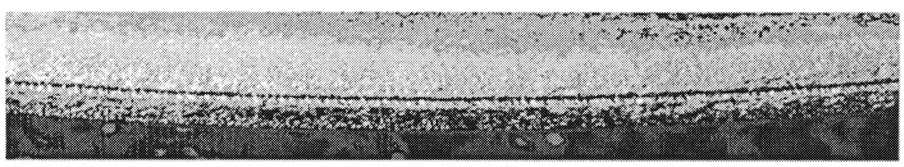


Fig.10. Photo of a tract on the tin cathode surface after 10^6 pulses.

The delivery of tin into track by liquid metal jet system and cathode surface regeneration system allow to avoid degradation of EUV light – as it is illustrated on fig.11. With this version of RDE source the EUV power 220W in 2π sr with BW=2% around 13.5 nm have been achieved during long time operation.

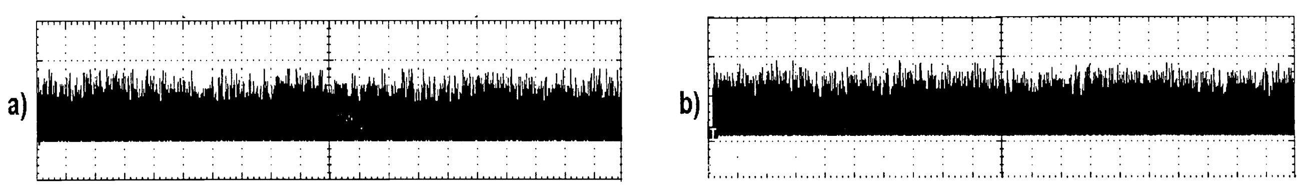


Fig.11. Sequences of the EUV pulses obtained at pulse repetition rate 4 kHz at start of the source operation (a) and after 10^6 pulses (b).

3.2. Version of the RDE source using a baths with liquid as a tin supply.

Figure 12 shows a drawing of the RDE source with tin supply by passing the rotating electrodes edge through a baths with liquid tin. The rotating electrodes are covered with a thin tin layer and in such a way deliver tin into the discharge region. Simultaneously, the liquid tin into the baths is used as a high-effective heat removal from electrodes. Besides, the baths with liquid tin are used also as the sliding contacts connecting pulse power circuit to rotated electrodes. The capacitors connected to RDE trough the liquid tin were placed inside the vacuum chamber for reduction the circuit inductance.

Photo of DPP source with laser initiation of tin vapor between the rotating disk electrodes is shown in Fig.13.

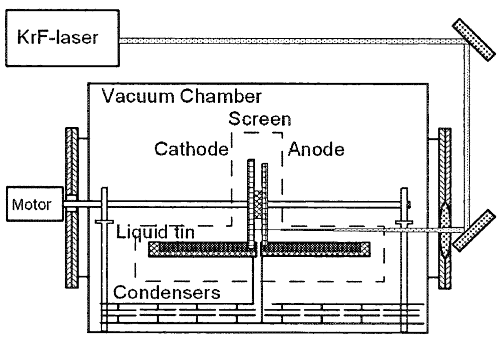


Fig.12.Version of RDE source with tin supply by passing rotating electrodes edges through baths with liquid tin

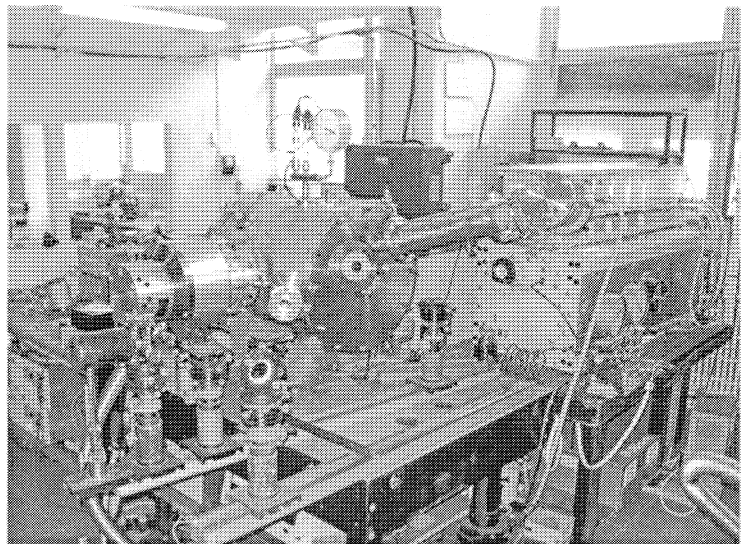
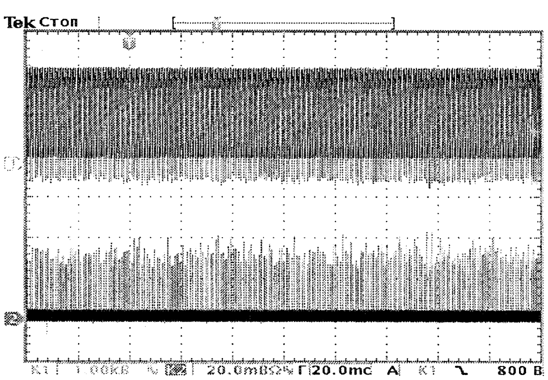


Fig.13. Photo of EUV source with rotated disk electrodes.



The experiment on study of a continuous RDE source operation with a pulse repetition rate of 1 kHz was carried out. In Fig.14 are given sequences of both applied voltage pulses and EUV signals after 1 hour of continuous source operation.

Fig.14. Oscilloscope traces of applied voltage and EUV signals at f=1 kHz.

4. CONCLUSION

The sources using Xe and Sn were investigated as potential tool for EUV lithography. In the DPP sources using Xe the achieved EUV power was 90 W in band in 2π sr at 2 kHz continuous operation and CE determined as the ratio of the EUV power, measured 1.2 m from the plasma pinch, to the electrical power dissipated in the discharge was around 0.5%. The electrode erosion measured after long time continuous operation of the EUV source using Xe at input power ~10 kW was determined in the range of (0.6 - 3.5) 10^{-7} g/pulse for our electrode configurations. In spite of electrode erosion, limiting source lifetime, Xe Z-pinch source can be successfully integrated in EUVL process line for resist testing, technology evaluation and to prepare EUVL for high-volume manufacturing[4,5].

The investigations of the DPP sources using Sn showed that CE achieves ~2% for the different methods of Sn vapor generation. The discharge in Sn vapors, initiated by excimer laser, remains an effective source of EUV radiation in rotating disk electrode configuration. This fact has allowed constructing the EUV source with rotating disk electrodes in which the average thermal load on the electrode surface decreased by several times in comparison with Xe source using a single discharge unit. The RDE source was shown to produce a plasma pinch of extremely small size: its diameter was determined as 0.29 mm (FWHM) and its length 0.54 mm. The RDE source was tested at the pulse repetition rate up to 4000 Hz. The EUV power measured at the distance of 1.2 m from the plasma pinch was of 220 W in band in 2π sr. Developing technology of DPP source with laser initiation of tin vapor between the rotating disk electrodes has shown a considerable promise to create the EUV source meeting the requirements of HVM EUV lithography.

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