INFLUENCE OF PLASMA NUCLEUS FORM ON RADIATION ORIENTATION IN HIGH-CURRENT PULSE PLASMA DIODE

A.F. Tseluyko[1], V.T. Lazurik[1], D.L. Ryabchikov[1], A. Hassanein[2], V.I. Maslov[1], I.V. Borgun[1], I.N. Sereda[1]
[1] V.N. Karazin Kharkov National University, Kharkov, Ukraine;
[2]Purdue University, West Lafayette, USA
E-mail: tselujko@htuni.kharkov.ua

The factors accompanied the generation directed super-radiation in high-current pulse discharge in tin vapor are investigated. Basing on measurements of space distribution of radiation intensity and fixing of discharge evolution phases images it was shown that generation of directed super-radiation occurs in the moment of plasma jet gushes from dense plasma formations situated close to the anode, and the orientation of super-radiation is the same as the plasma jet one. It was drown a conclusion about the presence of radiation-stimulated radiation effect in multiply ionized plasma.

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1. INTRODUCTION

The paper is concerned with creation of intensive radiation plasma source with the wave length $\lambda = 13.5$ nm for nanolithography. The radiation is formed due to recombination of multiply ionized tin atoms. The plasma creation and heating were performed in pulse plasma diode. It was shown in paper [1] that in such discharges at anode current density over 100 kA/cm^2 in dense plasma formations situated close to the anode the generation of powerful peaks of super-radiation in the range of wave lengths 12.2…15.8 nm and 50…200 ns in duration are occur. The peak radiation was observed in inductive phase of discharge evolution and took place in the first four half-cycles of discharge current. In [2] it was established that such radiation has strong orientation, which is different for different half-cycles of discharge current. The aim of present paper is to establish the connection of radiation orientation with the form of dense plasma formations in high-current pulse plasma diode in tin vapor.

2. EXPERIMENTAL SETUP

For studying of plasma column evolution dynamic the rapid system of image registration based on electron optical transformer (EOT) was used. The investigations were carried out by the way of single photographing of discharge gap in a fixed time moment using digital photo camera. The EOT was used as rapid light shutter due to pulse enabling voltage feeding V_F 20 ns in duration from illumination generator.

Simultaneously with fixing plasma column image the discharge current and voltage as well as intensity of radiation in the wave lengths 12.2…15.8 nm along and crosswise of the discharge were registered. The intensity measurement in this wave length was performed by semiconductor detector AXUV-20 with Mo–Si light filters. The discharge gap and systems of radiation intensity measurement were set in vacuum chamber, which pumped up to 10^{-6} Torr. The experimental setup is shown on Fig. 1.

The discharge gap includes a cathode with three ignitor rods, a needle anode and a coaxial current conduction system. For radiation withdrawal along discharge the cathode has a tube configuration. The outer cathode diameter was 1.1 cm, the inner one was 0.7 cm.

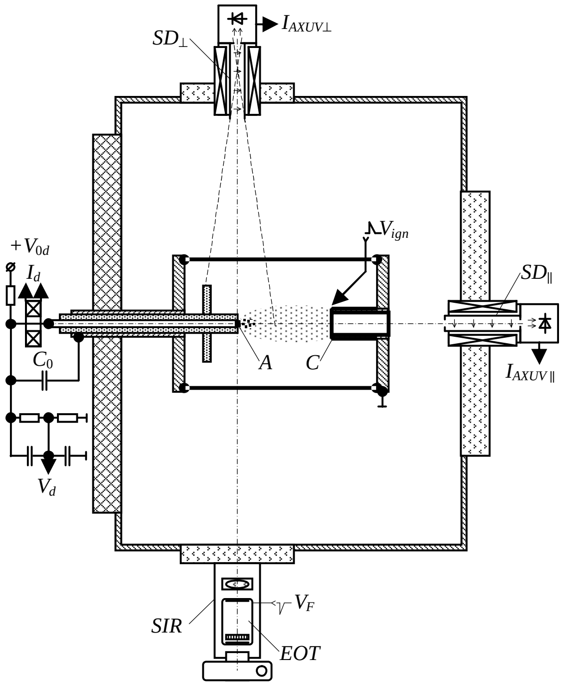

Fig. 1. The scheme of experiment. A – anode, C - cathode of discharge, $SD_\perp$ and $SD_\parallel$ – the systems of radiation measurement in the wave lengths 12.2 - 15.8 nm along and crosswise of the discharge accordingly, SFR – the system of image registration

The diameter of needle anode *A* was varied from 0.15 to 0.5 cm. For anode current concentration on the butt-end the anode side was covered by tube ceramic insulator. The sides and butt-ends of cathode and anode were covered with pure tin layer. The distance between cathode and anode was 5 cm.

The cathode and anode were attached immediately to capacitor with capacity of 2 µF, which charged up to voltages of 4…15 kV. At low pressure the discharge were ignited after discharge gap filling by initial plasma due to surface disruption on the cathode at pulse ignition voltage V_{ign}= 0.5…5.0 kV supplying.

At radiation intensity measurement by semiconductor detectors AXUV-20 the optical channel was protected from high-energy charge particle influence by built transverse magnetic field with intensity of 2 kOe with 25 cm in extent. The detectors were equidistant on distance of 42 cm from discharge zone. The detecting aperture of transverse detector grasped the whole zone of radiation generation.

3. RESULTS AND DISCUSSION

The maximum longitudinal orientation of peak super-radiation was observed at anode 0.15 cm in diameter using [2]. The oscillograms of discharge voltage and current, intensities of radiation along and crosswise the discharge are shown in Fig. 2. Here are presented the snapshots of the area situated close to the anode as well. The snapshots were made immediately before the peak of radiation, in the moment of radiation and 0.3 μs after it.

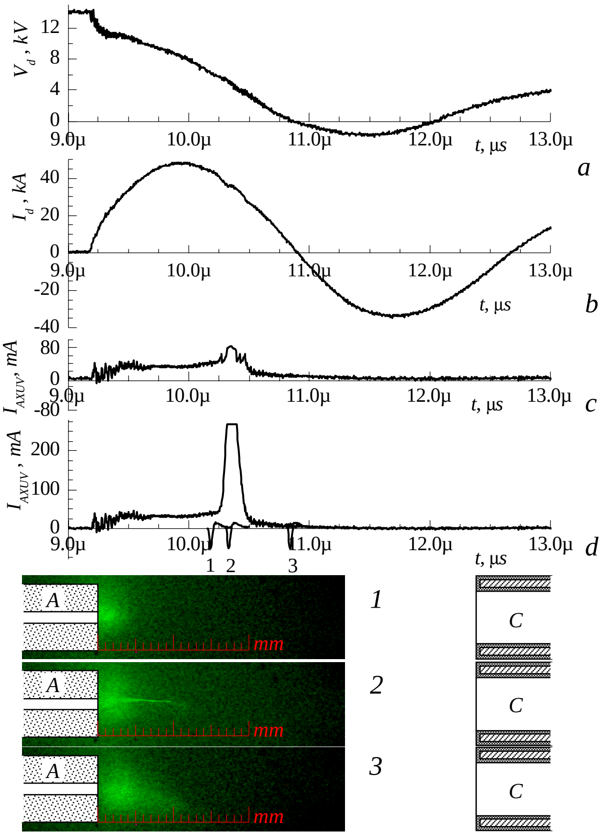

Fig. 2. The oscillograms of voltage (a) and current (b) of the discharge, intensities of radiation crosswise (c) and along (d) the discharge at V_{0d}= 14 kV, d_a=0.15 cm. (The light pulses of EOT 1-3 on oscillogram (d) are correspondent the snapshots of the area situated close to the anode 1-3)

One can see, that powerful peak super-radiation of strong longitudinal direction ($I_{\|}/I_{\perp}$~20) is observed in the 1st half-cycle of discharge current. Before the radiation peak the dense plasma situated close to anode has half-spheric form (snapshot 1). In the moment of peak radiation from the plasma toward the cathode the thin plasma jet ~0,05 cm in diameter and ~0.12 cm in length gushes (snapshot 2). After radiation peak this jet expanded up to diameter of ~0.3 cm.

For studying the forming conditions of the peak super-radiation in 2nd half-cycle the conditions of experiment were changed. According to paper [2] the peak radiation here is observed at discharge voltage 6…9 kV and at increased anode diameter. In this case after the main radiation peak in current maximum in 200 ns peak-satellite follows.

The oscillograms of discharge voltage and current, intensities of radiation in longitudinal and transverse direction and 5 snapshots of different discharge phases are shown in Fig. 3 as well. The 1st one is made before the beginning of main radiation peak, 2nd one is made in the moment of main radiation peak, 3rd one is made between the main peak and peak-satellite, 4th one is made in the moment of peak-satellite radiation, 5th one is made after peak-satellite radiation.

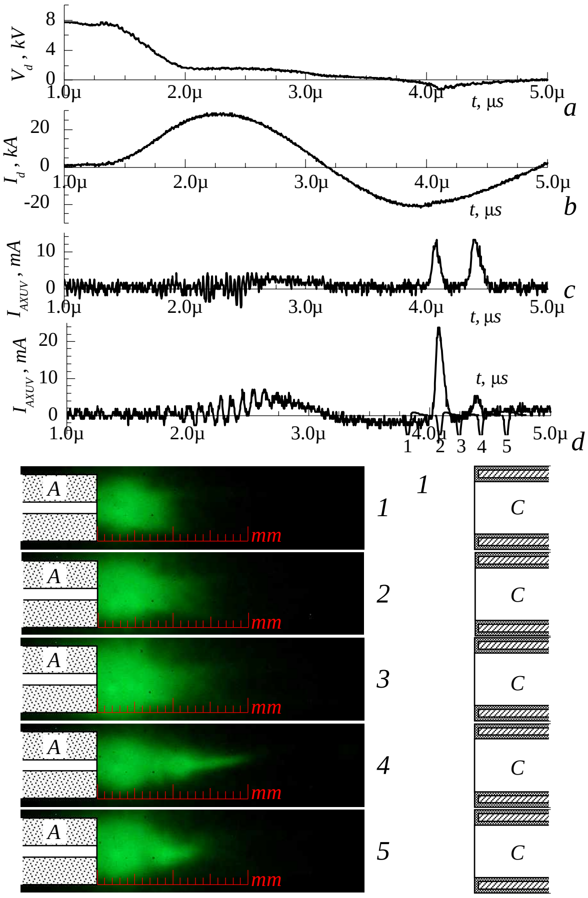

Fig. 3. The oscillograms of voltage (a) and current (b) of the discharge, intensities of radiation crosswise (c) and along (d) the discharge at V_{0d}= 8 kV, d_a=0.25 cm. (The light pulses of EOT 1-5 on oscillogram (d) are correspondent the snapshots of the area situated close to the anode 1-5)

One can see from the oscillograms of radiation intensities, that radiation of main peak has transverse direction and peak-satellite radiation has longitudinal direction. According snapshots 1 and 2 the super-radiation of main peak is generated in plasma nucleus of elliptic form. The snapshot 4 shows, that radiation of peak-satellite is accompanied with elongate plasma jet appearing. At this the intensities of peak-satellite radiation along the discharge exceeds crosswise one in 6 times.

For clearness the general discharge snapshot is shown in Fig. 4, where the whole radiation zones are visible: *1* – plasma situated close to anode, where recombination radiation generates; *2* – plasma jet, which generates peak super-radiation of longitudinal direction in the 1st half-cycle of discharge current; *3* – ellipsoid with generation of peak radiation of transverse direction in 2nd half-cycle; *4* – plasma jet, where the longitudinal radiation of peak-satellite generates.

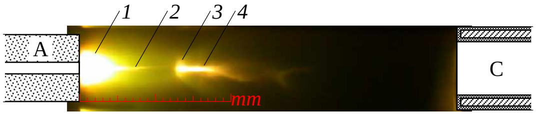

Fig. 4. The general snapshot of discharge gap with radiation generation zones

On the basis of presented data one can assume that super-radiation occurs at condition when magnetic shell stops keeping the hot dense plasma. Herewith the fast plasma expansion and drastical cooling-down happens. The dropping of electron temperature T_e leads to decrease of recombination flow neck depth ($\sim 3/2 \cdot T_e$) [3] and promotes the fast ion recombination.

Orientation of radiation apparently concerns with existence of mechanism of photon flow amplification in multiply ionized plasma (radiation-stimulated radiation effect). Then plasma elongation in some direction leads to strong increase of radiation intensity in this direction. (Estimation of photon path length with energy of 92 eV in plasma for our case gets the value of several millimeters that comparable with characteristic dimensions of dense plasma formations).

At availability of mechanism amplification of photon flow at flattened in longitudinal direction elliptical formations it will be generated the super-radiation of not high transversal orientation. In the elongated plasma jets it will be generated the radiation with strong longitudinal orientation.

4. CONCLUSIONS

In result of experiments it has been established, that orientation of super-radiation depends on elongation of plasma formation in this direction. The super-radiation appearing concerns with long plasma jet gush from plasma formation. The appearing of super-radiation is apparently associated with drastical plasma cooling down in the moment of plasma formation expansion. The correspondence of radiation orientation with form of plasma formation allows talking about existence of radiation-stimulated radiation effect in multiply ionized plasma.

REFERENCES

1. A.F. Tseluyko, V.T. Lazurik, D.L. Ryabchikov, V.I. Maslov, I.N. Sereda. Experimental study of radiation in the wavelength range 12.2-15.8 nm from a pulsed high-current plasma diode // *Plasma physics report*. 2008, v.34, N11, p. 1041-1046 (in Russian).
2. A.F. Tseluyko, V.T. Lazuryk, D.V. Ryabchikov, et al. The Dynamics and Directions of Extreme Ultraviolet Radiation from Plasma of the High-Current Pulse Diode // *Problems of Atomic Science and Technology. Series “Plasma Physics” (15)*. 2009, v.1, p.165-167.
3. Ye.L. Latush. Work principle and applying perspective of recombination plasma lasers // *Soros educational journal*. 1999, N 8, p.83-89 (in Russian).

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ВЛИЯНИЕ ФОРМЫ ПЛАЗМЕННОГО ЯДРА НА НАПРАВЛЕННОСТЬ ИЗЛУЧЕНИЯ В СИЛЬНОТОЧНОМ ИМПУЛЬСНОМ ПЛАЗМЕННОМ ДИОДЕ

А.Ф. Целуйко, В.Т. Лазурик, Д.Л. Рябчиков, А. Хассанейн, В.И. Маслов, Е.В. Боргун, И.Н. Середа

Исследуются факторы, сопровождающие генерацию направленного сверхизлучения в сильноточном импульсном разряде в парах олова. На основе измерений пространственного распределения интенсивности излучения и фиксации изображений фаз развития разряда показано, что генерация направленного сверхизлучения происходит в момент выброса струй плазмы из плотных прианодных плазменных образований, и направленность излучения совпадает с направлением плазменных струй. Сделан вывод о наличии в многократно ионизированной плазме эффекта радиационно-стимулированного излучения.

ВПЛИВ ФОРМИ ПЛАЗМОВОГО ЯДРА НА СПРЯМОВАНІСТЬ ВИПРОМІНЮВАННЯ В СИЛЬНОСТРУМОВОМУ ІМПУЛЬСНОМУ ПЛАЗМОВОМУ ДІОДІ

О.Ф. Целуйко, В.Т. Лазурик, Д.Л. Рябчиков, А. Хассанейн, В.І. Маслов, Є.В. Боргун, І.М. Середа

Досліджуються фактори, що супроводжують генерацію спрямованого надвипромінювання в сильнострумовому імпульсному плазмовому розряді в парах олова. На основі вимірювань просторового розподілу інтенсивності випромінювання і фіксації зображень фаз розвитку розряду показано, що генерація спрямованого надвипромінювання відбувається в момент викиду струй плазми з щільних прианодних плазмових утворень, і спрямованість випромінювання співпадає з напрямком плазмових струй. Зроблено висновок про наявність у багаторазово іонізованій плазмі ефекту радіаційно-стимульованого випромінювання.