DYNAMICS AND DIRECTIONS OF EXTREME ULTRAVIOLET RADIATION FROM PLASMA OF THE HIGH-CURRENT PULSE DIODE

A.F. Tseluyko, V.T. Lazuryk, D.V. Ryabchikov, V.I. Maslov, N.A. Azarenkov, I.N. Sereda, D.V. Zinov'ev, N.N. Yunakov, A.A. Makienko

V.N. Karazin Kharkov National University, Kharkov, Ukraine

The time behavior and orientation of radiation in the range of wavelengths 12.2…15.8 nm, which is generated in the high-current impulse plasma diode, working on tin vapor, are investigated in this paper. It is shown, that the intensive radiation in this range arises at an inductive stage of the discharge, it is multi-peak (τ_{pulse}~ 200 ns) and the near anode area is the region of its generation. The intensity and primary orientation of radiation depend on a discharge voltage and are various for different peaks.

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1. INTRODUCTION

The paper is devoted to creation of source of the directed extreme ultraviolet radiation, using the plasma radiation of the tin multi-charged ions in high-current impulse plasma diode for nano-lithography.

Usage of tin vapor, in comparison with gas-filling systems, allows exciting discharge under the super-low pressure conditions. It excludes excitation of the parasitic discharges and reduces losses of radiation in optical paths. Besides higher power efficiency of the source is predicted for the tin [1].

The purpose of the paper is to estimate the radiation generation region in the range of wavelengths 12.2…15.8 nm in high-current impulse plasma diode. In addition the dynamics and orientation of the radiation will be considered.

2. EXPERIMENTAL TECHNIQUE

The current in the diode is excited between the cylindrical electrodes, covered with tin, by the discharge of the capacity condenser of capacity 1 μF at starting pressure 2×10^{-6} Torr. The length of the discharge interval equals 5 cm, diameter of the cathode - 1 cm, diameter of the anode – 0.25 cm, the discharge voltage – 4…15 kV, the current amplitude – 5…35 kA, the current density on the anode – 0.1…0.7 MA/cm^2, half-cycle of current oscillations – 1.25 μs.

The lateral surface of the anode is covered by ceramic tube for discharge localization. The radiation output along the discharge is carried out through the central aperture in the cathode of diameter 0.7 cm.

The discharge ignition is performed after preliminary filling of a discharge interval by initial plasma due to surface discharge on the cathode, using a setting fire electrode. The impulse voltage 0.5…5.0 kV supplies on a setting fire electrode from the capacitor 0.025 μF through thyratron and inductance of value 400 μH.

The radiation in the range of wavelengths 12.2…15.8 nm is registered simultaneously along and across the discharge, using probe AXUV-20. There is possibility of spatial scanning of the discharge interval by the lateral probe.

3. EXPERIMENTAL RESULTS

It was found, that the intensive radiation in the range of wavelengths 12.2…15.8 nm arises at the inductive stage of the discharge, has multi-peak shape and the region of generation is the near anode area. The transversal dimension of the region of generation is comparable with the diameter of the anode, and its length changes depending on a discharge voltage and equals 0.5…1.0 cm. Fig. 1 shows the current, voltage of the discharge and radiation intensity in the range of wavelengths 12.2…15.8 nm across and along the discharge.

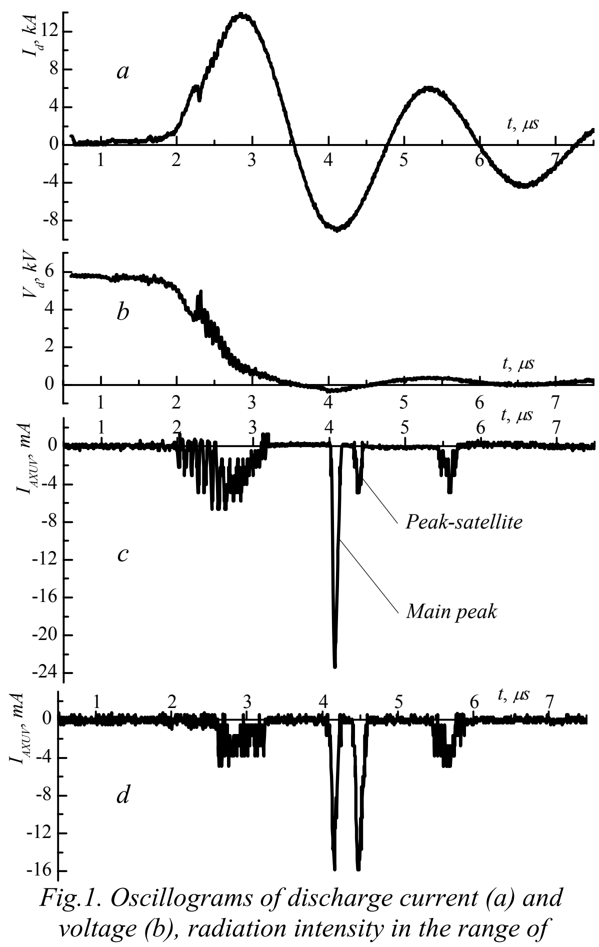

Fig.1. Oscillograms of discharge current (a) and voltage (b), radiation intensity in the range of wavelengths 12.2…15.8 nm across (c) and lengthwise (d) of the discharge at V_0= 6 kV

The wide pulse of radiation with relatively small amplitude registers, as a rule, during first half-cycle of discharge current oscillations. Its duration equals to half-cycle of current oscillations. When discharge voltage exceeds 10 kV the second narrow pulse with the duration of ~200 ns appears. Its intensity grows with increasing of the discharge voltage. This second pulse appears on a background of the wide pulse of radiation. More than 70% of energy, which is radiated during first half-cycle, is stored in a narrow peak pulse. The time of appearance of a narrow peak pulse depends on a setting of the fire voltage. (For higher voltage the peak pulse appears earlier.) The intensity of radiation along and across the discharge at the increased discharge voltage is demonstrated in Fig. 2. In this case the longitudinal component of radiation intensity for a narrow peak pulse more than in 50 times exceeds cross one.

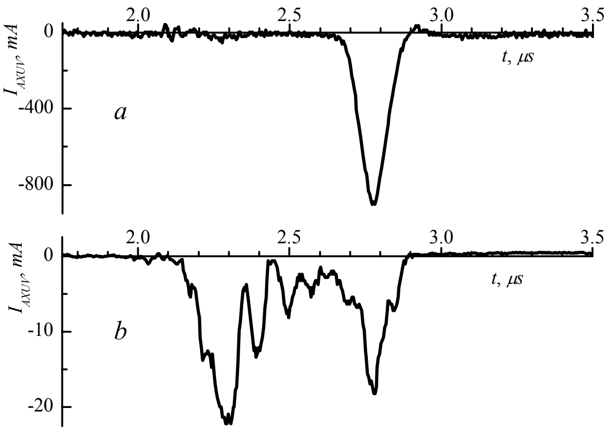

Fig.2. The intensity of the radiation in the range of wavelengths 12.2…15.8 nm during 1-st half-cycle of the discharge current along (a) and cross (b) to discharge at V_0= 13 kV

In the second and third half-cycles the pulses of radiation are extremely peaks (Fig. 1) with duration ~200 ns, it is much less than the half-cycle time. These radiation pulses always appear at the time when the current has its highest value. The radiation is accompanied by excitation of relative low-frequency fluctuations in a plasma column. The radiation peaks are registered when amplitude of the current exceeds 10 kA. Their intensity increases with growth of the discharge voltage. However they completely disappear when the discharge voltage becomes more than 10 kV.

In second half-cycle of the current oscillations an additional peak-satellite of duration ~200 ns, which followed the basic peak through 200 ns (Fig. 1), is observed besides the basic peak of radiation at discharge voltage 5…8 kV. The intensity of the peak-satellite also grows with increase of the discharge voltage. At voltage more than 8 kV the peak-satellite disappears.

The intensity and orientation of radiation in the range of wavelengths 12.2…15.8 nm in different half-cycles of the discharge current oscillations are different.

Fig. 3 demonstrates dependences of the ratios of the longitudinal and cross components of radiation intensity in the range of wavelengths 12.2…15.8 nm on the discharge voltage and setting fire voltage for first half-cycle of the discharge current. From the diagrams one can see essential increase of the longitudinal orientation of radiation with growth of the discharge voltage. We found the weak dependence of the radiation orientation on the setting fire voltage.

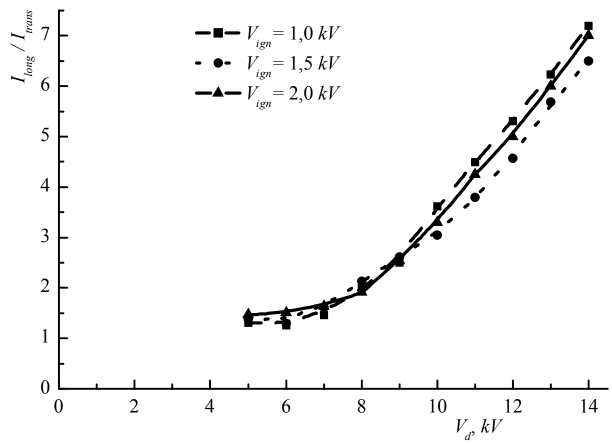

Fig.3. The dependence of ratio of longitudinal and transversal components of radiation intensities in the range of wavelengths 12.2…15.8 nm on discharge voltage and setting fire voltage for 1-st half-cycle of the discharge current

In Fig. 4 dependences of the radiation orientation of the basic peak in second half-cycle on the discharge voltage and the setting fire voltage are shown. The cross component of radiation increases with the discharge voltage growth (as against first half-cycle). The dependence of the radiation orientation on the setting fire voltage also remains weak.

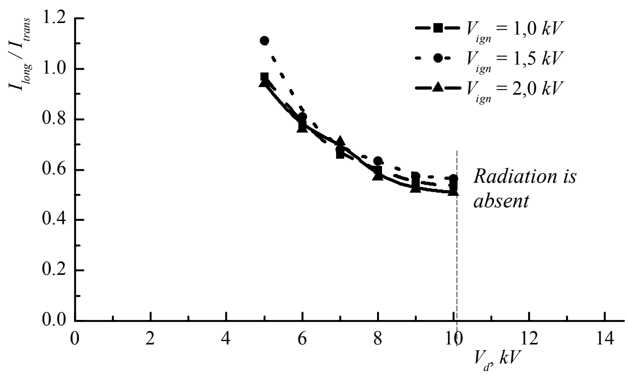

Fig.4. The dependence of ratio of longitudinal and transversal components of radiation intensities in the range of wavelengths 12.2-15.8 nm on discharge voltage and setting fire voltage for main peak of 2-nd half-cycle of the discharge current

Fig. 5 shows behavior of the radiation orientation of the peak-satellite depending on the discharge voltage and setting fire voltage. On the contrary to the basic peak the radiation of the peak-satellite (during second half-cycle) is essentially longitudinal, which grows with increase of the discharge voltage. The observed in experiments ratio of the longitudinal flow to cross flow is 10 for the peak–satellite.

4. DISCUSSION AND CONCLUSIONS

In high-current discharge in tin vapor the effect of generation of strongly anisotropic peak intensive radiation in the range of wavelengths 12.2…15.8 nm with radiation duration which is much shorter in comparison with half-cycle of discharge current oscillation is found out.

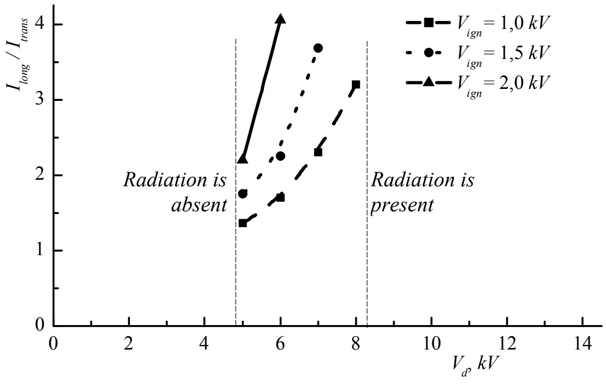

Fig.5. The dependence of ratio of longitudinal and transversal components of radiation intensities in the range of wavelengths 12.2-15.8 nm on discharge voltage and setting fire voltage for peak- satellite of 2-nd half-cycle of the discharge current

The dense near anode plasma with the length about 4-10 mm and diameter, which is close to the anode one, is a source of radiation for all half-cycles of the discharge. The dense plasma is formed from vapor of the anode material which is produced by an electron beam. The beam is accelerated by a double layer at the initial stage of the discharge [2].

During first half-cycle of discharge current oscillation with the energy J_{th} up to 50 J an isotropic radiation is generated. At J_{th}> 50 J on the background of the isotropic radiation during first half-cycle the peak with strongly anisotropic radiation, having an essential orientation along the discharge, appears. Before peak appearance the repeated formation of the double layer, leading to beam heating of plasma electrons, precedes. The longitudinal orientation, apparently, is connected with the geometrical factor (length of radiating near anode plasmas is more than its diameter).

At the energy J_{th} < 50 J in second and subsequent half-cycles peak radiation of mainly cross orientation is generated. Generation of radiation, apparently, is connected with adiabatic heating of plasma electrons at its compression by own magnetic field [3]. At the time adiabatic heating termination due to collisions the plasma electrons are cooled quickly. In addition an instability, which appears at this moment, induces intensive recombination radiation. At the energy J_{th} > 50 J peaks of radiation disappear.

Besides, in a narrow energy range in second half-cycle the peak-satellite of a longitudinal orientation is observed. This peak-satellite, apparently, as well as in first half-cycle could be associated with the geometrical factor.

We found some differences in orientation of radiation for various pulses. Their peak positions specify existence of several mechanisms of the peak formation of strongly anisotropic radiation in high-current discharge.

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ДИНАМИКА И НАПРАВЛЕННОСТЬ ЭКСТРЕМАЛЬНОГО УЛЬТРАФИОЛЕТОВОГО ИЗЛУЧЕНИЯ ИЗ ПЛАЗМЫ СИЛЬНОТОЧНОГО ИМПУЛЬСНОГО ДИОДА

А.Ф. Целуйко, В.Т. Лазурик, Д.Л. Рябчиков, В.И. Маслов, Н.А. Азаренков, И.Н. Середа, Д.В. Зиновьев, Н.Н. Юнаков, А.А. Макиенко

Исследуются временные характеристики и направленность излучения в диапазоне длин волн 12,2…15,8 нм, которое генерируется в сильноточном импульсном плазменном диоде, работающем на парах олова. Показано, что интенсивное излучение в этом диапазоне возникает на индуктивной стадии разряда, носит многопиковый характер ($\tau_{имп}$~ 200 нс), и зоной генерации служит прианодная плазма. Интенсивность и преимущественная направленность излучения зависит от разрядного напряжения и различна для разных пиков.

ДИНАМІКА І СПРЯМОВАНІСТЬ ЕКСТРЕМАЛЬНОГО УЛЬТРАФІОЛЕТОВОГО ВИПРОМІНЮВАННЯ З ПЛАЗМИ СИЛЬНОСТРУМОВОГО ІМПУЛЬСНОГО ДІОДА

О.Ф. Целуйко, В.Т. Лазурик, Д.Л. Рябчиков, В.І. Маслов, М.О. Азарєнков, І.М. Середа, Д.В. Зінов'єв, М.М. Юнаков, А.А. Макієнко

Досліджуються часові характеристики і спрямованість випромінювання в діапазоні довжини хвиль 12,2...15,8 нм, що генерується в сильнострумовому імпульсному плазмовому діоді, який працює на парах олова. Показано, що інтенсивне випромінювання в цьому діапазоні виникає на індуктивній стадій розряду, носить багатопіковий характер ($\tau_{імп}$~ 200 нс), і зоною генерацій служить прианодна плазма. Інтенсивність і переважна спрямованість випромінювання залежить від розрядної напруги і відмінна для різних піків.