Lead evaporation by VUV radiation of various spectral ranges

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Abstract. The results of an experimental study of the plasma formed by the evaporation of the lead target in the field of powerful broadband VUV radiation are presented. A pulse light-erosion magnetoplasma compressor (MPC’s) discharge is used as a model source of VUV radiation. “Gas filtration” of radiation is used to control the spectral composition – the discharge takes place in pure inert gases: in argon at 200 torr and neon at 400 torr. This allows us to manage the spectral distribution of radiation energy and to limit the energy of quants which irradiate the lead target with the first ionization potential of buffer gas. Shadow photography, toeplergrathy, double exposure laser holographic interferometry are used for diagnostics. Experimentally established different distribution of parameters in the lead plasma depending on the spectral composition of the impact radiation (the composition of buffer gas). It is shown that when the energy of quants increases (above the lead second ionization potential), a more even heating of the plasma layer is realized.

1. Introduction
Since the 1950s there has been a rapid increase in interest in the physical problems associated with the measurement and use of vacuum ultraviolet radiation. On the one hand, it became possible to send scientific instruments beyond the absorbing atmosphere of the Earth, which allows us to study the radiation of the Sun, stars and interstellar space in the far ultraviolet region of the spectrum [1, 2]. On the other hand, in the last decade a number of technical methods have been developed by which extremely high temperatures can be achieved under laboratory conditions [3, 4]. The phenomena arising at high temperatures serve either as a direct object of study in the far ultraviolet region, or as sources of radiation for other research tasks [5, 6]. In addition, it was found that many problems of solid state physics can be significantly helped by the study of several aspects of the vacuum ultraviolet radiation interaction with various materials [7-11].

2. Experimental setup
The experimental setup was a cylindrical vacuum chamber, in which a source of radiation and plasma flows was installed. As a source of radiation was used the discharge of "magnetoplasma compressor" (MPC), which was a system of two electrodes (AISI 304) of coaxial-torsion geometry, separated by ablative plasma-forming dielectric sleeve (caprolon) [9, 12, 13] in which a high-temperature (plasma focus) is formed on the axis near the central electrode.

The plasma, radiating and electrical properties of this type of MPC have been well studied, and are presented in a number of articles and reports [9, 11, 14], which describe both the features of the
discharge itself, with a good 70...90% efficiency, and high-spectral- bright characteristics in the UV and VUV spectrum areas with 40...60% light efficiency.

The power source was the pulsed high-voltage capacitor switched by tiratron. Capacitor stored energy is 1.0-3.6 kJ ($C_0 = 18 \mu F$, $U = 10-20$ kV, the maximum current is up to 170 kA). A rectangular sample (50×30×10 mm) is set with a long side lengthways the discharge. The position of the sample is 45 mm from the axis and 10 mm from the face of MPC (figure 1). Such placing additionally allows us to control the energy of falling radiation along the length of the sample.

The discharge takes place in pure inert gases: in argon at 200 torr and neon at 400 torr. Optical diagnostics was carried out using the Toepfer Schlieren scheme in the light-field mode and double-exposure laser holographic interferometry [15], which was implemented based on a solid-state Nd:YAG laser (Solar LQ-115 with wavelength $\lambda = 532$ nm). According to the obtained interference lines it is possible to determine what processes took place during the experiment.

It is important to note that the MPC discharge emission has characteristic spectral and temporal features. During the first 3-5 µs, until the plasma focus is formed, the discharge radiates in the visible range. Under its influence the sample is heated and evaporated. Thus, a vapor layer of the target material appears above the surface. Subsequently (after 5 µs) a plasma focus is formed, which radiates in the VUV region of the spectrum. “Gas filtration” of radiation is used to control the spectral composition. This allows us to manage the spectral distribution of radiation energy and to limit the energy of quanta which irradiate the lead target with the first ionization potential of buffer gas. Therefore, the energy of the radiation quanta that affected the lead sample was limited to 20 eV in neon and 14.5 eV in argon. In this case, the first lead ionization potential $I_{Pb} = 7.4$ eV, the second – 15.03 eV. When the plasma focus radiation reaches the surface of the sample, the vapors are ionized with no buffer gas ionization. The photoionization causes plasma formation, which, expanding, creates a “plasma piston”, above which there is a layer of shock-compressed buffer gas and a shock wave (figure 1).

3. The results
Interferograms makes it possible to determine the parameters of both the shock wave and the shock-compressed layer and the plasma layer formed from the sample material vapor as a result of photoionization. Figure 2 shows the interferograms of the gas-plasma layers above the lead surface at the time of 10 µs after the start of the discharge. Figure 2 (a) – discharge in neon, 2 (b) – in argon.

Figure 3 shows one interference fringe from figures 2 (a) and 2 (b) (marked with the white arrows), and the line corresponding to the position of the “vacuum” fringe is also plotted. The section above point A is the course of the interference band in the background gas. The segment AB demonstrates...
the density jump in the shock wave. The segment BC indicates that the background gas in this region is compressed by the “plasma piston”, but, since the angle of slope of the segment is small, we can say that the pressure in it changes weakly in height. CD corresponds to the contact boundary between the shock-compressed gas and the target vapor plasma. In this region, there is a sharp change in temperature due to a change in composition (plasma – shock-compressed gas). The DEFG curve shows the change in the refractive index \((n - 1)\) in the lead vapor plasma (more precisely, in the vapor-plasma layer), reflects the complex dependence of the thermodynamic parameters of the plasma on the height above the target.

![Figure 2](image)

**Figure 2.** Interferogram of the lead evaporation in neon (400 Torr) (a) and in argon (200 Torr). Discharge characteristics: 20 kV, \(I_{\text{max}} = 164\) kA, \(C = 18\) \(\mu\)F. The arrow shows the direction to discharge.

![Figure 3](image)

**Figure 3.** Interference lines in different media (a – neon, b – argon) with certain shifts relative to vacuum.

From the assumption that the contact boundary moves at speeds lower than the local speed of sound, let us assume that the process is isobaric. Then, for example, for band 10 in neon, the background gas is compressed about \(V_1/V_0 = 1.3\) times, which follows from a comparison of the SW and CB fronts positions (figure 3). Similarly in argon \(V_1/V_0 = 1.5\). Taking the adiabatic index \(\gamma = 1.44\), let’s determine the pressure of the shock-compressed layer [16]:

\[
p_1 = \frac{(\gamma + 1)(\gamma - 1)V_0 \cdot V_{-1}}{(\gamma + 1)V_0 - (\gamma - 1)} p_0.
\]

Thus, the shock gas pressure in neon is \(7.9 \cdot 10^4\) Pa, in argon \(4.8 \cdot 10^4\) Pa.

The band shift allows us to determine the refractive index because \((n - 1) = \Delta k \lambda/L\), and the refractive index is determined:

\[
(n - 1) = \left[2\pi \sum \alpha_i N_i - 4.49 \cdot 10^{-14} \lambda^2 \alpha_e \right] n_0
\]
$\alpha$, cm$^3$ is the dipole polarizability of the atom (ion) [17]; $N_i$ is the fraction of the x-sort of atoms or ions in the plasma ($N_i = n_i/n_0$); $\alpha_c$ is the degree of plasma ionization ($\alpha_c = n_c/n_0$), and $n_0$ is the plasma concentration.

Assuming that the contact boundary moves at velocities less than the local speed of sound, we assume that the pressure in the high-temperature region is almost constant [18]. Then, assuming that the pressure in the plasma layer does not change significantly, in the approximation of local thermodynamic equilibrium, we determine the temperature change along the height. For this purpose, for each point of the interference band we select the temperature corresponding to the obtained shift—corresponding to the obtained change in the refractive index (formula (2)). Retrieved temperature distributions are shown in table 1.

| Table 1. Temperature in the plasma layer. |
|------------------------------------------|
| Position | Temperature (kK) | Argon | Neon |
|----------|-------------------|-------|------|
| D        | 4.25              | 5.9   |
| E        | 4.7               | 7.22  |
| F        | 5.65              | 7.32  |
| H        | 5.31              | 7.27  |

Thus, the internal energy of the plasma at the discharge in Ne is about 1.5 times greater than for the discharge in Ar. This is due to the fact that when discharged in Ne, the energy of the VUV radiation quanta is sufficient for double ionization of lead.

**Conclusion**

Temperature height distributions in the plasma layer above the lead surface during its evaporation by VUV radiation of different spectral composition were determined. Thus, in the neon medium the temperature changes from 7.2 kK at the contact boundary to 7.3 kK inside the plasma layer and drops to 5.9 kK at the surface of the sample, while the concentration of particles in the plasma changes in the range $(0.7-1.2) \times 10^{18}$ cm$^{-3}$. Temperature changes from 4.25 kK at the contact boundary to 5.65 kK inside the plasma layer and drops to 5.3 kK at the surface of the sample when discharged in argon. The internal energy of the lead plasma during the discharge in Ne is 1.5 times higher than for the discharge in Ar. This is explained by the fact that in the case of the discharge in Ne the absorption in the vapor is carried out not only by atoms (as in Ar), but also by single ions of Pb.

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**References**

[1] de Wit T D, Kopp G, Fröhlich C and Schöll M 2017 *Geophys. Res. Lett.* **44** 1196–203  
[2] Zheng W, Jia L and Huang F 2020 *iScience* **23** 101145  
[3] Vyacheslavov L et al 2018 *Physica Scripta* **93** 035602  
[4] Zimin A M, Krupin V A, Troyon V I and Klyuchnikov L A 2015 *Phys. Atom. Nucl.* **78** 1319–25  
[5] Bakshi V 2006 *EUV Sources for Lithography* (Bellingham: SPIE Press)  
[6] Chkhhalo N I and Salashchenko N N 2009 *Nucl. Instrum. Meth. A* **603** 147–9  
[7] Astashynski V M, Dzahnidze H M, Kostyukevich E A, Kuzmitski A M, Shoronov P N, Shlymanski V I and Uglov V V 2020 *High Temp. Mater. P–us* **24** 99-107  
[8] Arkhipov V P, Kamrukov A S, Kozlov N P and Makarchuk A A 2016 *Prikladnaia fizika* **6** 102-
8 [in Russia]

[9] Protasov Yu S, Protasov Y Y, Telekh V D and Shchepanyuk T S 2014 *Encyclopedia of Low Temperature Plasma. Plasma aerodynamics* Vol IX-4 (Moscow: Yanus-K) pp 383–436 [in Russian]

[10] Skurat V 2003 *Nucl. Instrum. Meth. B* 208 27–34

[11] Kamrakov A S, Kozlov N P, Protasov Yu S and Shashkovskii S G 1989 *High Temp.* 27 141–55

[12] Pavlov A, Protasov Yu, Telekh V D and Tshepanuk T 2017 *J. Phys. Conf. Ser.* 830 012062

[13] Nosov K V, Pavlov A V, Protasov Yu Yu, Telekh V D and Tshepanuk T S 2018 *J. Phys. Conf. Ser.* 1115 032011

[14] Protasov Yu S 1991 *Radiative plasmadynamics* vol 1 (Moscow: Energoatomizdat) [in Russian]

[15] Pavlov A V, Protasov Yu Yu, Telekh V D and Shchepanuk T S 2019 *E H Worksh* 11 111–25

[16] Raizer Yu P 2011 *Introduction to Fluid Dynamics and Shock Wave Theory for Physicists* (Dolgoprudny: Publishing House Intellect) [in Russia]

[17] Schwerdtfeger P and Nagle J K 2019 *Mol. Phys.* 117 1200–25

[18] Braginskii S I 1958 *J. Exp. Theor. Phys.* 34 1068–74