ENERGY LOSSES OF FAST LIGHT IONS AND PLASMON EXCITATION IN METAL FILMS

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In this paper, we present the results of measurements of the secondary emission electrons (SEE) coefficients and electron energy distributions in the forward and backward directions. The measurements were carried out in experiments with three different substances. Generalizing the results obtained makes it possible to determine the mechanisms for energy losses of a fast ion propagating in solid-state plasma. The present investigation is dedicated to thick silver foil ionoluminescence study under different incident angles and proton energies also. Possible mechanisms of light generation are discussed based on obtained experimental data.

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1. ANISOTROPY OF THE ENERGY TRANSFER FROM AN ION

In the energy spectrum of the SEE we can distinguish between three electron groups.

1. Slow electrons with energies $E < E_p$, where $E_p = h\omega_p$ is the energy of the plasma oscillations with frequency ω_p. These electrons are produced from the ionization by plasma oscillations and from direct collisions with large impact parameters, accompanied by small momentum transfers.
2. Moderate-energy electrons, which are produced exclusively in direct collisions accompanied by moderate momentum transfers.
3. Fast electrons, which move preferentially in the propagation direction of the ion. These are convoy electrons and δ-electrons, which produced from direct collisions with small impact parameters, accompanied by large momentum transfers. The velocity convoy electrons, coincides in magnitude with the velocity of the ion, $v_e = v_p$, and has the same direction. The velocity of the δ-electrons that corresponds to the maximum possible momentum transfer can be defined as $v_\delta = v_p\cos\theta$, where v_p is the velocity of a bombarding ion and the angle θ is measured from its propagation direction.

Since a fast primary ion transfers a substantial fraction of its energy to the electrons that move in its propagation direction (convoy electrons and δ-electrons). We can speak of the anisotropy energy transfer from an ion.

The coefficient of SEE γ is proportional to dE/dx - specific ionization losses of ion. This fact was proved theoretically and experimentally.

Experiments aimed at investigating the anisotropy of the energy transfer from a fast ion were carried out on a device which described in detail in [1]. A 5.15-MeV α-particle flow with the intensity $I_{\alpha 0} = 4.64 \times 10^6$ particles per second was emitted by the Pu^{239} radioisotope source. α-particle flow penetrated target (3) and reached massive collector (5), made of the same material as the target. The targets were in the form of foils of thickness 5.6 μm (Al), 2.01 μm (Cu), and 0.27 μm (Ni). A voltage of 300 V of either polarity was applied between the collector and the target. The forward (γ_F) and backward (γ_B) emissions were measured.

The coefficient γ was determined from the formula:

$$\gamma_F = 2\frac{k_F I_{\alpha 0} + I_c}{k_F I_{\alpha 0}}, \quad \gamma_B = 2\frac{I_c - k_F I_{\alpha 0}}{k_F I_{\alpha 0}} \qquad (1)$$

where $I_{\alpha 0}$ is the current of α-particles from a radioisotope source and k_F is the fraction of α-particles that have passed through the target. The ratio R of the forward SEE coefficient γ_F to the backward one γ_B

$$R = \gamma_F / \gamma_B, \qquad (2)$$

was measured to be 1.57 for aluminum, 1.69 for copper, and 1.82 for nickel. According to these data, the ratios R for different substances differ insignificantly, by no more than 10% of the mean value.

Rothard and his colleagues [2] carried out experiments with a carbon target and with Li^{2+} ions, which are close in mass, energy, and charge state to α-particles used in our experiments. An analysis of the above results from our measurements and of the data from Rothard experiments of allows us to suggest that the ratio R is close to each other for different target substances. This factor was equal approximately 1.7. Hence, the δ- and convoy electrons can carry away approximately 22-29 % of the energy that the ion transfers to the electrons in different substances.

2. ENERGY DISTRIBUTION AMONG DIFFERENT ELECTRON GROUPS

A steady-state nonequilibrium power-law electron distribution function in a solid-state plasma was formed when the ion-induced SEE takes place. It was shown theoretically and experimentally [3, 4]. This function is $N(E) = AE^{-s}$, where s is the power index and A is a constant, E is the total electron energy in a solid body $E = \varphi + E_F + eU$, where φ is the work function, E_F is the Fermi energy, and the energy eU is measured in the vacuum.

The energy of the electrons produced in ionization by the wake-field oscillations cannot exceed E_p. Consequently, slow electrons produced in this ionization process are distributed in the emission spectrum over its low-energy part bounded from above by the plasmon energy.

Under conditions close to those mentioned above, we experimentally measured the energy spectra of the electrons produced from the forward SEE induced in a beryllium foil by 4.9-MeV α-particles [4] (see *Fig. 1*). The experimentally obtained power-law energy spectrum may be divided into two parts, the boundary between which is determined by the energy E_p = 18.9 eV of a plasmon within the beryllium target.

We separately integrate these two parts of the experimental emission spectrum N(E) over energy and determine the number N_1 of electrons from the first group and the number N_2 of electrons from the second group for beryllium:

$$N_1 = \int_{\varphi+E_F+eU}^{E_p} N(E)\sqrt{E}dE \quad , \quad N_2 = \int_{E_p}^{\varphi+E_F+E^*} N(E)\sqrt{E}dE \qquad (3)$$

where E* = 100 eV.

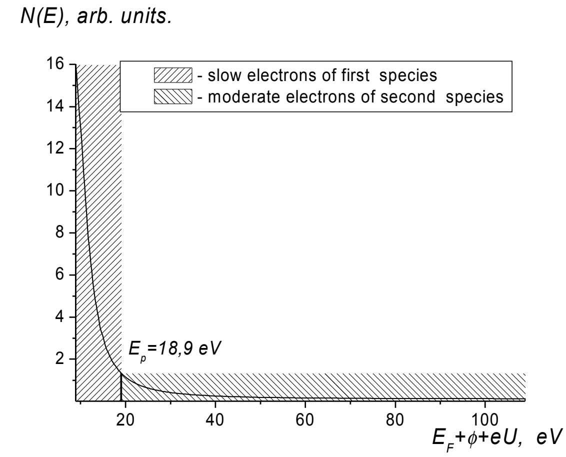

Fig.1. The energy spectrum of secondary electron emission induced by 4.9 MeV α-particle from beryllium foil

The fractions of the energy lost by the ion to the electrons from the first and the second group can be estimated as the ratios of N_1 and N_2 to the total number $N_0=N_1+N_2$ of the emitted electrons:

$$K_1 = N_1 / N_0 = 0.63 \quad \text{and} \quad K_2 = N_2 / N_0 = 0.37. \qquad (4)$$

A charged particle moving in a solid-state plasma is lost through the following two dissipation mechanisms: first, in direct collisions accompanied by small momentum transfers and, second, by the excitation of plasmons. The fraction of energy that goes into the production of slow electrons ($E < \hbar\omega_p$) can be defined as:

$$\Delta E_{slow} / \Delta E = K_1(1 - R_\delta). \qquad (5)$$

In the case at hand, this fraction, which is transferred to electrons by the above two mechanisms, is from 45 to 49 % of the total energy lost by an ion in the substance.

Theoretically, it is estimated that a fast particle moving with velocity **v** expends a comparatively large fraction of its energy on the excitation of collective oscillations [5]:

$$\Delta E_k / \Delta E = \ln(v / 10v_0) / 2\ln(v / v_0), \qquad (6)$$

where ΔE_k is the fraction of energy that has gone into the excitation of collective oscillations, ΔE is the total energy loss of a fast charged particle in a solid-state plasma, and v_0 is the Bohr orbital velocity of an electron in a hydrogen atom in the ground state. In our opinion, this formula somewhat overestimates the fraction of the energy lost to the wake waves: $\Delta E_k/\Delta E \approx 40$ %. We think that energy losses of fast ions in solid are divided between such channels (see *Fig. 2*).

3. LIGHT EMISSION

The measurements of the luminescence induced by ions from the silver foil were carried out using the experimental setup described in detail in [6]. The proton beam with energies from 0.8 MeV to 2.4 MeV fell on the target. The incident angle α was ranged between 20^0 and 70^0 with respect to the target normal. The silver sample thickness was equal 3,2 μm. Silver has modified plasma resonance in ultraviolet region ($\hbar\omega_p$=3.78 eV, λ=330 nm [*7*]). Quartz condenser projected the optical radiation from the target surface on the entrance slit of the grating monochromator.

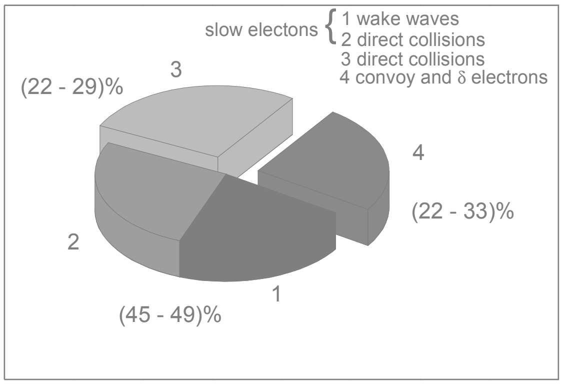

Fig.2. Distribution of energy losses of fast ions in a solid between different channels of energy transfer

Detection of light was performed using the photomultiplier detector in the wavelength region 250 to 700 nm. The axis of the optical system was put at the angle of 90° with respect to the beam, i.e. α+β=90°, where β is observation angle.

Typical silver ionoluminescence spectra are presented on *Fig. 3*. It consists of one wide band with maximum near 326 nm. Maximum location and bandwidth on half-height were almost invariable under all angles α. Moreover, there was investigated radiation intensity with wavelength λ = 326 nm dependence on incident angle for both foil sides. These dependences are presented on *Fig. 4* for proton beam energy of 1,6 MeV.

It is seen that under increase of angle α radiation intensity steadily increases. It's valid for both foil sides. For the range 20° ≤ α ≤ 45° radiation intensity from the foil front side is higher, than from the back side. For incident angle larger than 45° anomalous radiations increase is observed from the foil backside. Under α ≥ 55° radiation intensity from the backside becomes higher than from the front side. Similar results were obtained for all using ion energies.

Following known mechanisms of light generation with charged particles have to be considered:

a) transition radiation,

b) bremsstrahlung,

c) volume plasmon radiation decay,

d) surface plasmon radiation decay on surface roughness.

Without a doubt, transition radiation is present in silver ionoluminescence from front side. The bremsstrahlung contribution to ionoluminescence can be neglected, because estimations from [8] showed that in used proton energy range transition radiation intensity is much higher than this of bremsstrahlung even when α =70°. Moreover, we founded that the plasmon radiation make contribution in this light band, especially for medium and large incident angles.

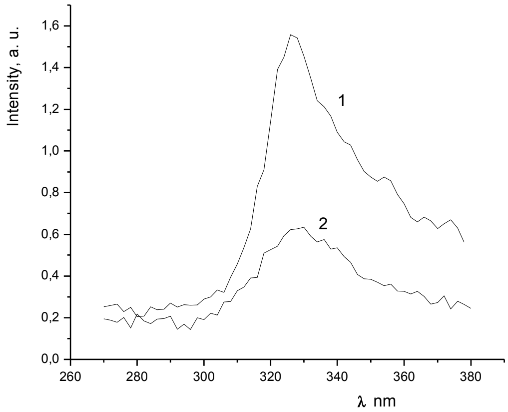

Fig. 3. Ionoluminescence spectra of silver induced by proton with energy 2.4 MeV: 1 – front surface, 2 – back surface. Incidence angle α=45°

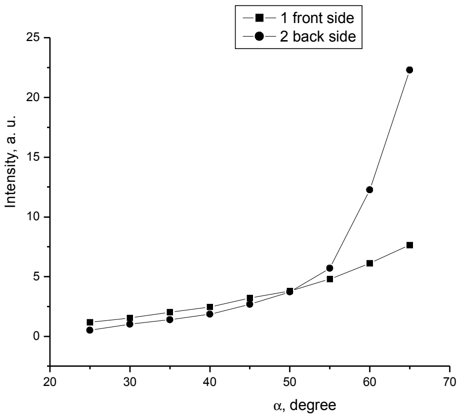

Fig. 4. Experimental incidence angle dependence of ionoluminescence (proton energy 1.6 MeV): 1 – front surface, 2 – back surface

Transition and plasmon radiation also make the contribution to luminescence radiation from foil back side. It's valid for small and medium angle α values. For high incident angles the anomalous radiation intensity increase is observed (see *Fig. 4*), comparably to foil front side. This can be explained by the existence of another one luminescence mechanism. This radiation was associated, to surface plasmon radiation decay on roughness.

CONCLUSIONS

According to the above analysis of the results obtained, the observed anisotropy of the ion-induced SEE is presumably associated with the fraction of energy that is carried away from the medium by both convoy electrons and δ-electrons. In addition, it has been noted that plasma oscillations excited by an ion have a substantial impact on the production and emission of electrons.

For the silver target the main contribution to light yield is made by the following mechanisms. For small proton angles – it's transition radiation. For medium angles – it's plasmon mechanism. For large output angles – it's plasmon mechanism and surface plasmon radiation decay.

As SEE, as ionoluminescence dates show that plasmon generation have important part in transmission of ion energy to media and generation secondary particles as electrons and photons.

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ПОТЕРИ ЭНЕРГИИ БЫСТРЫХ ЛЕГКИХ ИОНОВ И ВОЗБУЖДЕНИЕ ПЛАЗМОНОВ В МЕТАЛЛИЧЕСКИХ ПЛЕНКАХ

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В этой работе представлены результаты измерений энергетических распределений электронов и коэффициентов вторичной ионно-электронной эмиссии на прострел и на отражение. Эксперименты проведены для трех веществ. Обобщение полученных результатов позволило определить механизмы потерь энергии быстрыми ионами, движущимися в твердотельной плазме. Настоящая работе также посвящена изучению ионолюминесценции толстой серебряной фольги при различных углах падения и энергиях протонов. Исходя из полученных экспериментальных данных обсуждаются возможные механизмы генерации света.

ВТРАТИ ЕНЕРГІЇ ШВИДКИМИ ЛЕГКИМИ ІОНАМИ ТА ЗБУДЖЕННЯ ПЛАЗМОНІВ В МЕТАЛЕВИХ ПЛІВКАХ

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У цій роботі представлені результати вимірів енергетичних розподілів електронів і коефіцієнтів вторинної іонно-електронної емісії на простріл і на відбиття. Експерименти проведені для трьох речовин. Узагальнення отриманих

результатів дозволило визначити механізми втрат енергії швидкими іонами, що рухаються у твердотільній плазмі. Ця робота також присвячена вивченню іонолюмінесценції товстої срібної фольги при різних кутах падіння та енергіях протонів. Виходячи з отриманих експериментальних даних обговорюються можливі механізми генерації світла.