EMISSION OF LIGHT BY METALS BOMBARDED BY NONRELATIVISTIC ELECTRONS

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The results of an experimental study of the emission of light by metals in the optical region of the spectrum under bombardment by nonrelativistic electrons are discussed. The emission is found to be polarized and depends on the state of the target surface and its dielectric properties. The polarized component of the radiation can be explained by the theory of transition radiation. The unpolarized part may be due, on the one hand, to the excitation of surface waves and, on the other, to the emission of radiation by electrons encountering random inhomogeneities on the surface (this is the analog of the Smith-Purcell radiation for periodic inhomogeneities).

In a previous paper [1] it was suggested that it would be desirable to investigate the radiation due to charged particles incident on the surface of a metal at different angles. Moreover, it was reported that the emission of radiation by electrons passing through thin films of metals ($a \ll \lambda$) at different angles (up to 75° from the normal to the surface of the film) was completely due to transition-radiation photons. The experimental data for this case are in good agreement with theoretical predictions obtained for the transition radiation from a thin plate.

The present paper is a direct continuation of [1] and reports data on the radiation from thick metal targets exposed to electrons with energies up to 100 keV and different angles of incidence on the surface of the metal. Visible and ultraviolet radiation were analyzed (λ = 2800–5800 Å) from Al, Au, Cu, Ge, Pt, and In bombarded by electrons. Measurements were made of the polarization, spectral composition, and angular distribution of the radiation as well as of its intensity as a function of electron energy, beam current, time of surface bombardment, angle of incidence of the electrons, and optical constants of the metals. We confine ourselves to data for electrons entering the target at angles ψ = 0–75° to the normal. Cases corresponding to ψ greater than 75° were classified as glancing collisions with the target and will be analyzed in a separate paper. Thus, at first sight, artificial separation of the data was introduced for good reasons. The point is that, when ψ lies between 0 and 75°, most of the resultant emission consists of transition-radiation photons, whereas for $\psi > 75°$ and, especially, for angles close to $\pi/2$ the transition radiation practically disappears and another mechanism is responsible for the generation of the radiation. The above separation of the data is therefore found to facilitate their analysis.

The surfaces of the metal targets were subjected to careful polishing (insofar as this was possible for each metal). The polished surface was then coated with a layer of the same material by vacuum evaporation to a thickness not less than 1 μ. One of the existing methods [1] was used to determine the optical constants of the specimens (the refractive index n and the absorption coefficient k), which are necessary for the computation of the theoretical curves to be compared with experimental results. The experimental arrangement and the basic definitions and notations are the same as in [1] and will not, therefore, be described here.

Figure 1 shows the spectral density of the radiation (W) as a function of φ for Au, Cu, Pt, and Ge (φ is the angle between the plane of transmission of the polarizing filter and the plane of observation). The data were determined for variants C and D and different angles of entry of the electron into the target (ψ). In all cases, the radiation emitted was found to be linearly polarized and, in individual cases, the degree of polarization was high, reaching 90–95%. As in the case of thin films [1], when the plane of observation and the plane of emission are parallel (variant D), the electric vector of the wave always lies in the plane φ = 0° whatever the direction of entry of the electron into the target. If, on the other hand, these two planes do not coincide (variant C), the plane containing the electric vector of the wave is shifted relative to the φ = 0° plane, and the magnitude of this shift is in agreement with that expected from

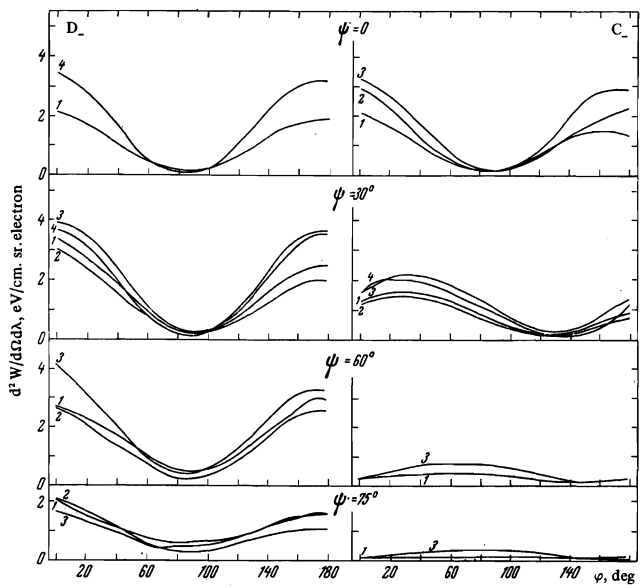

FIG. 1. Spectral density of the emitted radiation as a function of the angle φ for E = 80 keV, λ = 5000 Å for: 1–Au; 2–Cu; 3–Pt; 4–Ge. C_–θ = 127.5°; D_–θ' = –52.5°.

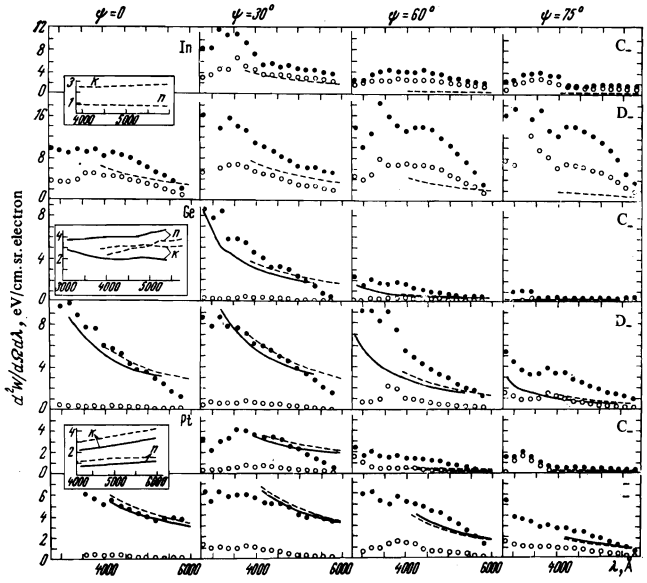

FIG. 2. Spectral density of the emitted radiation for In, Ge, Pt for E = 80 keV; ●–$W_{\parallel}$, ○–$W_{\perp}$; C_–θ = 127.5°; D_–θ' = –52.5°.

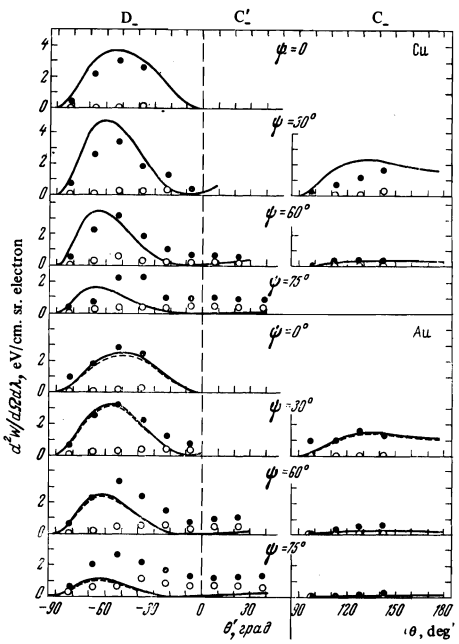

FIG. 3. Angular distribution of the spectral density of the emitted radiation for Cu and Au when E = 80 keV, λ = 5000 Å: ●–$W_{\parallel}$, ○–$W_{\perp}$.

the theory of transmission radiation. The polarized part of the radiation is identifiable with the transition radiation. We have measured the spectral density of the radiation both for waves polarized in the plane of emission ($W_{\parallel}$) and for waves polarized in the plane perpendicular to it ($W_{\perp}$).

The spectral distributions of the emitted radiation for In, Ge, and Pt are shown in Fig. 2. The figure also shows our own measurements of the optical constants of these metals (broken curves) and those taken from the literature (solid curves)[2-6]. The experimental results are compared with the predictions of the transition-radiation theory[7]. In all the figures the dotted curves represent the transition-radiation theory based on our own measurements of the optical constants, and the solid curves show the theoretical results based on the optical constants obtained by other workers. The calculated perpendicular component $W_{\perp}$ should appear only in the variant C and was, in fact, found to be very small so that it is not shown in the figures.

As the wavelength increases, the spectral density is found to fall and its functional behavior is largely determined by the optical constants of the material. If we compare the difference $W_{\parallel} - W_{\perp}$ with the theory, we find that, in most cases, there is good agreement with experiment. A similar situation obtains in the case of the angular distribution (Fig. 3), the spectral density as a function of electron energy (Fig. 4), and the spectral density as a function of the angle of entrance of the electron into the target (Fig. 5). The only exception is presented by In and other metals for large angles of entrance of the electrons into the metal. The perpendicular component $W_{\perp}$ turns out to be definitely greater than the experimental background, and increases with increasing electron energy (Fig. 4) and angle of entrance of the electron into the target (Fig. 5), and has a pecular angular distribution. For example, for In the intensity maximum on the $W_{\perp}$ curve is observed in the direction of the normal to the target.

If we ignore surface phenomena, then $W_{\perp}$ may consist of bremsstrahlung and luminescence. $W_{\parallel}$ should additionally contain the transition radiation. The bremsstrahlung and luminescence yields should decrease with increasing electron energy. In point of fact, bremsstrahlung is connected with the scattering of electrons, and the probability of scattering in a thin layer decreases with increasing energy. Since the light emitted by the metal can leave only from a thin surface layer, the bremsstrahlung yield should be inversely proportional to the electron energy. The same obtains for the luminescence which appears on the surface film of the metal. One would expect that the brightness of this luminescence not only does not increase but, on the contrary, decreases with increasing electron energy because the ionization energy losses of a particle in the surface layer decrease with increasing particle velocity. It would therefore appear that the data can be represented as the sum of two terms, namely, a term proportional and a term inversely proportional to the electron energy. The former can be interpreted as being due to the transition radiation and the latter as bremsstrahlung and luminescence.

This type of analysis has been carried out by many workers (including ourselves in our previous papers), but it now appears to us that this procedure is doubtful for a number of reasons.

Firstly, estimates which we have carried out on the basis of bremstrahlung formulas for an absorbing medium[7] show that the bremsstrahlung intensity under our experimental conditions is, on the average, lower by an order of magnitude than the experimental background, which amounts to about 0.2 eV/cm-sr-electron. The measurements should not, therefore, contain the bremsstrahlung component. A comparable, very small contribution to the resultant emission is provided by interference between bremsstrahlung and transition

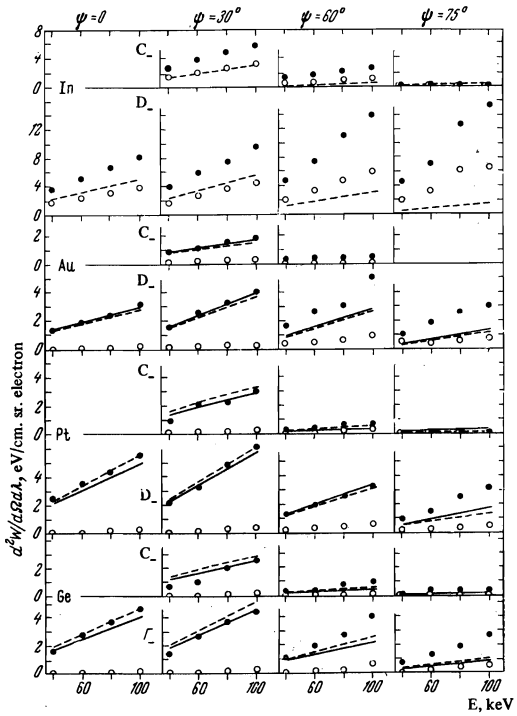

FIG. 4. Spectral density of the emitted radiation as a function of the particle energy E for λ = 5000 Å: ●–$W_{\parallel}$, ○–$W_{\perp}$; C_–θ = 127.5°, D_–θ' = –52.5°.

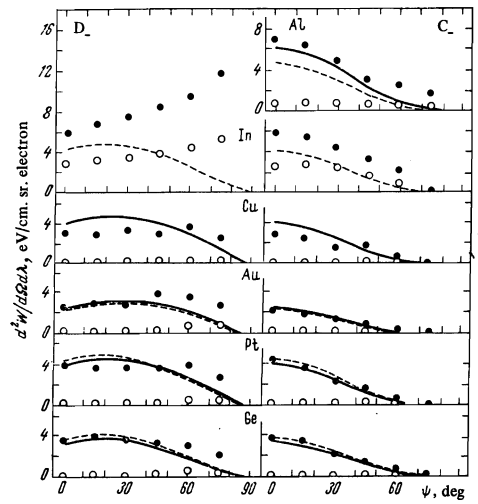

FIG. 5. Spectral density of the emitted radiation as a function of the angle of entrance ψ for E = 80 keV, λ = 5000 Å: ●–$W_{\parallel}$, ○–$W_{\perp}$, C_–θ = 127.5°, D_–θ' = –52.5°.

radiation. We note that the formulas given in[7] were obtained only for the case of normal incidence of the electron on the target, and it may be supposed that for an oblique incidence the results will be different in absolute magnitude. However, the observed increase of $W_{\perp}$ with electron energy (Fig. 4), and the totally random dependence of this intensity on the atomic number of the material, exclude the possibility of the transition radiation. The first of these two reasons also excludes luminescence (there are no formulas which can be used to estimate the absolute intensity of the luminescence).

Secondly, if the electrons generate only the transition-radiation photons, the appreciable multiple scattering of the electrons may lead to the appearance of the perpendicular component of the radiation. In fact, this is clearly seen in Fig. 1 when, for example, one investigates the emission of radiation in variant D, and $W_{\perp}$ is measured at $\varphi = 90°$. For an electron which has undergone appreciable scattering in the vertical plane over the coherent length of the radiation, the geometry of the experiment then becomes equivalent to variant C for the entrance angle ψ equal to the angle of scattering. For $\varphi = 90°$ and large values of ψ one may then record an appreciable intensity of the transition radiation which is identified as the perpendicular component. In such cases, as the electron energy increases there should, on the one hand, be a change in the root-mean-square angle of multiple scattering and, on the other hand, there should be an increase in the intensity of the transition radiation. It is, therefore difficult to conclude which particular energy dependence should be shown by that part of $W_{\perp}$ which is due to this effect. Our estimates have shown that $W_{\perp}$ observed in the experiment cannot be due to multiple scattering.

The theory of transition radiation with which the experimental results were compared is based on the assumption of a perfectly smooth separation boundary between the media. The surfaces of the targets which we have investigated, on the other hand, are not, of course, ideal. Surface roughness may lead to the depolarization of the transition radiation because the electrons cross the separation boundary at all possible angles ψ. If the plane of observation is fixed, changes in the position of the plane of emission with the angle ψ would then lead to the appearance of the perpendicular component of the radiation. In other words, the photons may transfer from $W_{\parallel}$ to $W_{\perp}$ but the total energy $W_{\parallel} + W_{\perp}$ should either remain the same or should change only slightly.

At the same time, the experimental data show that the measured total intensity of the emission, especially for large angles of entrance of the electron into the target, may exceed the expected intensity of the transition radiation by a substantial factor. Figure 2 shows that this is particularly well defined for the In target, whose surface cannot be made smooth and is seen to be rough by visual inspection. However, this excess of radiation is observed not only for In but also for Ag and all the other metals when the target surfaces are artificially made to be rough. The behavior of surfaces which are definitely rough will be discussed separately. We shall merely note here that, in such cases, one observes a weakly polarized radiation for large entrance angles into the target in the case of many metals, and the magnitude of this intensity is high in comparison with the transition-radiation intensity. Moreover, "natural" roughness is difficult to avoid even when special polishing procedures are used.

Similar data have been discussed in the literature during the last few years[8-11] for silver. For oblique or, more precisely, almost glancing incidence of the electron on the surface of silver, it was found that there was a high-intensity emission in the wavelength region around about 3500 Å, and this could not be explained within the framework of the transition radiation

theory.[8,9] Some workers[8,10] relate this radiation to the excitation of surface plasma waves (because of surface inhomogeneities these waves can be emitted into vacuum). Other workers[9,11] have put forward the bremsstrahlung mechanism. The radiation has an intensity maximum whose position does not coincide with the transparency band of silver (~3250 Å) and is shifted somewhat toward longer wavelengths; it corresponds to the position of the intensity maximum for the excitation of the surface waves[7] (this conclusion is valid for a nonabsorbing medium). The calculated intensity due to the excitation of surface waves[7] for the metals which we have investigated, including silver, shows that the experimentally observed radiation cannot be explained in terms of the generation of surface waves, either according to the absolute magnitude of the intensity or to the other functional dependences. Since absorption in these metals is relatively high, surface waves can provide only a small contribution to the total emission.

In view of the foregoing, it seems to us that it is possible that another generation mechanism is, in fact, operative in this case.[12] Thus, an obliquely moving electron traverses a portion of its path near the point of entry into the metal in the immediate neighborhood of the target and may radiate as a result of interactions with the random surface irregularities. This radiation has long been known as the Smith-Purcell radiation in the case of regular, one-dimensionally periodic inhomogeneities.[13] A detailed account of this phenomenon is given in[14,15]. According to these papers, the yield of this radiation is relatively high, and if one supposes that our specimens contain inhomogeneities whose surface density is only a fraction of a percent of that discussed in[14,15], then the radiation intensity which we have measured can be satisfactorily explained. The fact that the radiation originates from the random surface inhomogeneities rather than periodic inhomogeneities should affect mainly the polarization of the radiation, the angular distribution, and the spectral composition, but not the total radiated energy. The final solution of this problem will be possible only after the corresponding theory has been constructed. No such theory is available at present.

The results of the present experiments thus lead to the following main conclusion: the emission of radiation by metals bombarded by electrons consists of the transition radiation and the radiation due to surface irregularities; depending on the direction of entrance of the electron into the metal, one or other of the generation mechanisms will predominate.

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