Radiation by electrons due to roughness of a metallic surface

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A study has been made of the radiation in the optical portion of the spectrum on entry of nonrelativistic electrons into metals. Targets of various metals with polished and rough surfaces were used. Analysis of the data leads to the conclusion that such radiation mechanisms as bremsstrahlung, luminescence, and surface wave generation do not make an important contribution to the total radiation and that it consists of transition radiation and radiation at surface irregularities. Depending on the angle of entry of the electron into the target and the state of the surface, one or the other mechanism predominates.

1. In recent years many experiments [1-10] have been carried out on the radiation in the optical portion of the spectrum arising on entry of electrons into metals. Together with the polarized part of the radiation (transition radiation), as a rule, unpolarized (excess) radiation of high intensity is observed. For Ag, when electrons hit the surface at grazing angles, [2-7] the intensity of excess radiation turns out to be two to three orders of magnitude higher than the expected intensity of transition radiation. Some authors [4-7] suggest that the excess radiation is due to bremsstrahlung or luminescence of the surface layer of the metal under the action of the electrons. Other authors [2,3] associate the excess radiation for Ag with the production of surface plasmons. All of these discussions have only a qualitative nature and the problem of excess radiation remains unsolved up to the present time.

The results of our studies [8,9] for thin films ($a \ll \lambda$) of Ag, Al, Au, and Cu and for electron entry angles into the target $\psi \leq 75^\circ$ (the entry angle ψ is measured from the normal to the target surface) show that their radiation under the action of electrons is polarized, the polarization being that predicted by the theory of transition radiation. In this case the condition $W_\parallel \gg W_\perp$ is always satisfied, where $W_\parallel$ is the intensity of radiation polarized in the plane formed by the direction of viewing and the normal to the target surface—the plane of radiation, and $W_\perp$ is the intensity of radiation polarized in the perpendicular plane. The degree of polarization of the radiation $P = (W_\parallel - W_\perp)/(W_\parallel + W_\perp)$ reaches 97%. The value of $W_\perp$ in almost all cases is less than the experimental background. Sometimes, mainly at large entry angles ($\psi = 60-75^\circ$), the two intensities become comparable. The experimental data on all of the characteristics agree with satisfactory accuracy with the conclusions of the theory of transition radiation for plates, and the contribution of other forms of radiation does not exceed the background radiation.

The radiation by electrons entering polished massive samples [8-10] of metals (Ag, Al, Au, Cu, Ge, In, Pt) is also polarized, but the degree of polarization depends substantially on the electron entry angle. For small angles of entry the degree of polarization reaches ~ 95%; with increase of the entry angle it drops to ~15–20%. This is due to the comparatively large value of $W_\perp$, whose absolute magnitude increases with increasing electron energy, and also with increase of the entry angle ψ. The angular and spectral distributions of $W_\perp$ differ qualitatively from the similar distributions for transition radiation. For some metals (Ag, Al) the absolute value of $W_\perp$ exceeds the noise level by two to three orders of magnitude or more. The radiation component mentioned comprises the excess (unpolarized) portion of the radiation by electrons on entry into a metal and does not have any relation to transition radiation.

The parallel component of the radiation ($W_\parallel$), in addition to excess radiation, contains transition radiation. For small entry angles (ψ equal to 0° and 30°), where $W_\perp$ is small, the parallel component is satisfactorily explained by the theory of transition radiation in all of its characteristics, including the absolute intensity. With increasing entry angle up to $\psi = 60-75^\circ$, the value of $W_\perp$ increases and only the difference $W_\parallel - W_\perp$ agrees with the theory of transition radiation.

Analysis of these data shows that the excess radiation cannot be explained by bremsstrahlung and luminescence. The intensity of bremsstrahlung by an electron in an absorbing medium, calculated for the metals specifically studied by means of the equations for the case of normal entry [11], are on the average an order of magnitude smaller than the experimental background and two to three orders of magnitude smaller than the measured intensity of radiation. The equations for bremsstrahlung for oblique entry of electrons into an absorbing medium are not available, but the conclusion drawn is confirmed by the observed difference in the radiation by electrons in thin films and massive samples of the same metal, the substantial rise in the yield of radiation with increasing electron energy, and the completely random dependence on the atomic number of the material.

From consideration of the results it follows that the additional radiation is due to surface irregularities. In fact, the surfaces of thin films obtained by thermal evaporation of a metal onto a thin collodion base are smooth and for them the additional radiation is absent and only transition radiation is observed. In massive samples whose surfaces are obtained by evaporation of a metal onto a polished massive base and contain statistically distributed irregularities, intense additional radiation is observed together with the transition radiation.

At the present time we can mention two mechanisms of radiation production due to surface irregularities. The first is the excitation of surface waves which are converted into transverse waves as the result of scattering by irregularities. This interpretation is given for the data on silver in refs. 2 and 3, where no quantitative comparison is made of the experimental data with the theory developed for the specific values of the optical constants of silver, but a qualitative conclusion is drawn on the basis of the theoretical results [12] for a nonabsorbing medium. It is apparent that the excitation energy of surface waves in this case will be greater, the greater the time during which the electron interacts with the surface. In fact, calculations for a nonabsorbing medium show that the energy of the surface waves is inversely proportional to $\cos\psi$ (to the angle of incidence $\sin i \approx 1$) and the electron energy.

Quite different results are obtained in calculation, for the specific values of the optical constants of the metals studied, of the spectral density of excitation energy of surface waves by electrons of various energies moving toward the target surface at angles $\psi = 0-88.5°$ according to the equation [13] for an absorbing medium. Comparison of the experimental data of refs. 8 and 10 with the results of these calculations shows that, first, additional radiation is observed for all metals studied, including metals whose dielectric permittivities do not correspond to the conditions of excitation of surface waves (Ge); for some metals (Al) the radiation has turned out to be more intense than Ag, in spite of the fact that the best conditions for excitation of surface waves in the spectral interval studied exist just for Ag. Second, the experimentally observed radiation is not explained by surface wave production either in its absolute intensity or in its various functional dependences. As a result of the fact that the absorption in the metals studied is comparatively large, surface waves can give only a minor contribution to the total radiation, particularly at grazing angles of entry. In an absorbing medium the intensity of excitation of surface waves for grazing angles of entry is two to three orders of magnitude smaller than for $\psi = 0°$. The statement made in refs. 2 and 3 would be valid if the value of $\operatorname{Im}\epsilon$ were $\sim 10^{-2}$, whereas the minimum value of $\operatorname{Im}\epsilon$ of all of the metals studied is in silver in the region $\lambda \approx 3500$ Å and amounts to 0.24.

2. Accordingly it appears to us that another, more efficient mechanism may exist for production of the radiation [8] associated with movement of an electron above a surface. Actually an electron moving obliquely traverses some portion of its path near the point of entry into the metal close to the surface and can radiate at the irregularities existing on this surface. There are no specific theoretical studies of the radiation of an electron entering at an arbitrary angle into a metal whose surface contains randomly distributed irregularities (or of an electron in flight above such a surface). On the other hand, similar radiation for periodically placed nonuniformities has been known for a long time (radiation by an electron moving above a diffraction grating) under the name Smith-Purcell radiation. [14] This radiation has been studied in detail experimentally and theoretically [15,16] for diffraction gratings with metallic covering at grazing angles of electron entry into the grating. It is evident that the radiation at surface irregularities will be more efficient for grazing angles of electron entry into the surface.

In order to confirm this idea we undertook an experiment on the radiation arising on electron entry at angles $\psi = 75-88.5°$ into targets of Ag, Al, Au, and Ge having polished (P targets) and rough (R targets) surfaces. The latter are ordinary matte surfaces for which the size of the irregularities is of the order of the wavelengths of the spectral region studied and the surface density of these irregularities provides visual diffuseness of the surface. The results of these studies are shown in Figs. 1—5. Details of an experimental nature have been given previously [9] and are omitted here. For a comparison we have shown also the data for $\psi = 0°$ and the theoretical curves expected for transition radiation (solid curves).

In the case of P targets and for $\psi > 75°$ radiation is detected (Ag, Al) whose intensity increases with increasing electron energy and entry angle. For grazing entry angles the radiation intensity is greater than the intensity of transition radiation in the case $\psi = 0°$ and also exceeds its expected value for these entry angles by 10^2-10^3 times. For large entry angles the degree of polarization of the radiation drops substantially ($P \approx 15-20\%$) in comparison with the case of small angles (ψ equal to 0, 30°) where $P \approx 85-95\%$, and the polarized part of the radiation is explained in every respect by the theory of transition radiation. For tar-

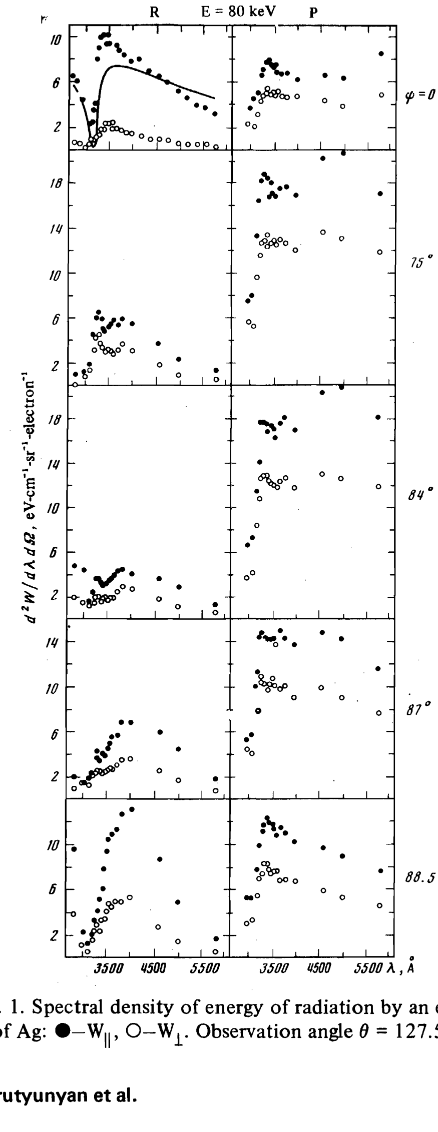

FIG. 1. Spectral density of energy of radiation by an electron in targets of Ag: ●—$W_{\parallel}$, ○—$W_{\perp}$. Observation angle $\theta = 127.5°$.

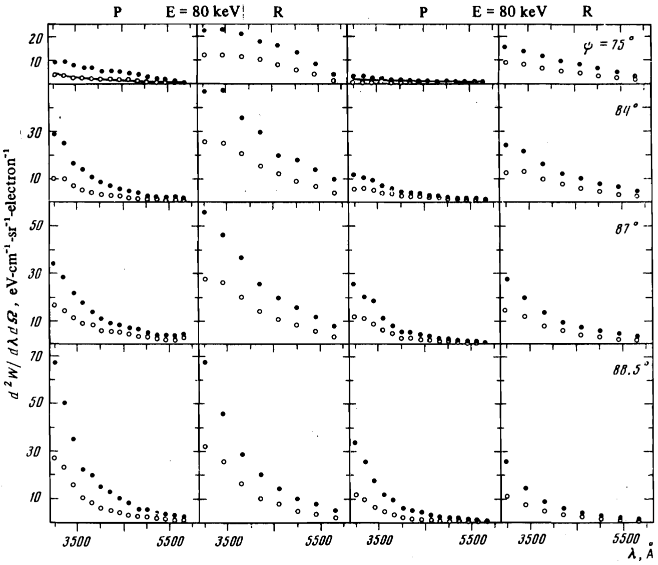

FIG. 2. Spectral density of energy of radiation by an electron in targets of Al: ●—$W_{\|}$, ○—$W_{\perp}$; $\theta = 52.5°$.

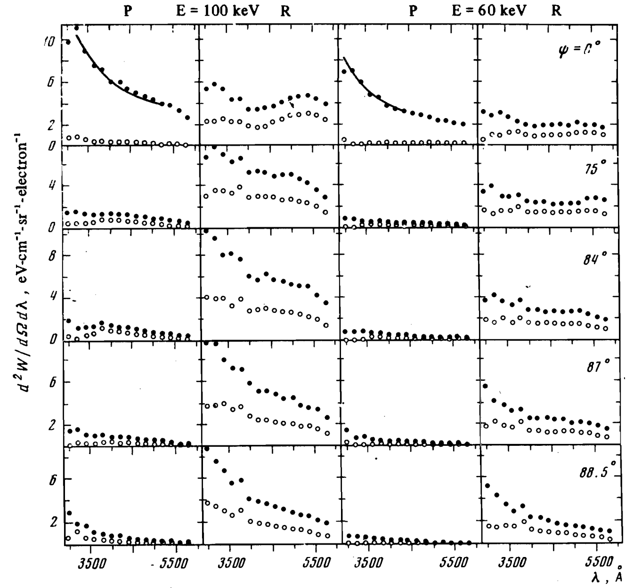

FIG. 3. Spectral density of energy of radiation by an electron in targets of Ge: ●—$W_{\|}$, ○—$W_{\perp}$; $\theta = 127.5°$.

gets of Ge (Fig. 3), whose surfaces can be well polished, the radiation at grazing entry angles is small.

For R targets, as a rule, the degree of polarization is smaller and the radiation intensity many times greater than for P targets. For ψ equal to 0° and 30°, the degree of polarization falls to ~20—40%, and the total energy of radiation changes only slightly; in individual cases it exceeds the energy of transition radiation for P targets by 1.5—2 times. Here, in addition to depolarization of the transition radiation, a spectral redistribution of the radiant energy occurs. With increasing entry angle the degree of polarization of radiation by electrons in R targets changes only slightly and remains at a level ~20—40% (Figs. 4 and 5); however, the energy of radiation rises substantially and reaches maximum values for ψ = 75—84°. At these entry angles the intensity of the radiation is many times greater than the intensity of transition radiation at ψ = 0°. In the transition to small grazing angles (ψ equal to 87° and 88.5°) the intensities for R and P targets (Ag, Al) gradually become comparable. The impression is that the electron moving at grazing angles does not react at large irregularities which exist on the surface of R targets and at which it reacts at a less inclined entry. At the same time the electron reacts at irregularities of smaller size, which exist to the same degree on P and R target surfaces. This recalls the well known effect in optics in which a matte surface at a grazing view angle appears glossy. The intensity of radiation by electrons at R targets increases with increasing electron energy; the spectral distributions are determined by the optical constants of the metal, and the energies of the radiation emitted in different directions are about the same.

The results of the present experiment leave no doubt that an electron can produce high intensity radiation at surface irregularities; at the present time the possibility exists of comparing them only with the results of investigations of Smith-Purcell radiation.[15,16] The radiation spectra measured in Refs. 15 and 16 in the visible portion of the spectrum for gratings with an aluminum covering can be divided into two parts, coherent and amorphous. The first part consists of narrow intensity peaks whose locations are determined by the condition of coherent additions due to periodic nonuniformities (the Purcell condition). The second part is a continuous spectrum due to fluctuations in the periodicity and, apparently, to additional random irregularities of smaller size which always exist on the grating surface. The energy of the radiation of the amorphous part is rather large, amounting to 60—70% of the total radiation energy.

The experimental data obtained by us for aluminum at grazing entry angles agree with the amorphous part of the radiation observed in the experiments mentioned in absolute intensity, spectral composition ($\lambda^{-5}d\lambda$), and also in the dependence of the radiation intensity on entry angle and electron energy. Theoretical calculations[16] show that the intensity of Smith-Purcell radiation is very high. In order to explain that part of the radiation energy which is observed in the present experiment, it is sufficient to assume that the surface density of irregularities of the R targets used by us amounts to only a fraction of a percent of the density of irregularities of a grating.

Note that, in the sense of total energy of radiation over a broad spectral interval, the data for targets with randomly distributed irregularities should not differ substantially from the data for targets with ordered irregularities. The variable step for targets with randomly distributed irregularities will lead to nonfulfillment of the condition of coherent addition of the radiation from different nonuniformities, the discreteness of the radiation harmonics will disappear, and the radiation energy in a peak will be smeared over the entire spectrum. In addition, if we take into account that random irregularities will have different configurations and furthermore that the surface nonuniformity is two-dimensional (for a diffraction grating it is one-dimensional), a substantial depolarization of the radiation will occur. The fact that such a trivial mechanism of radiation production by electrons has not been discussed up to the present time in interpretation of the data for Ag is evidently due to the fact that data existed only for Ag, for which there are certain qualitative bases for associating this radiation with surface plasmons.

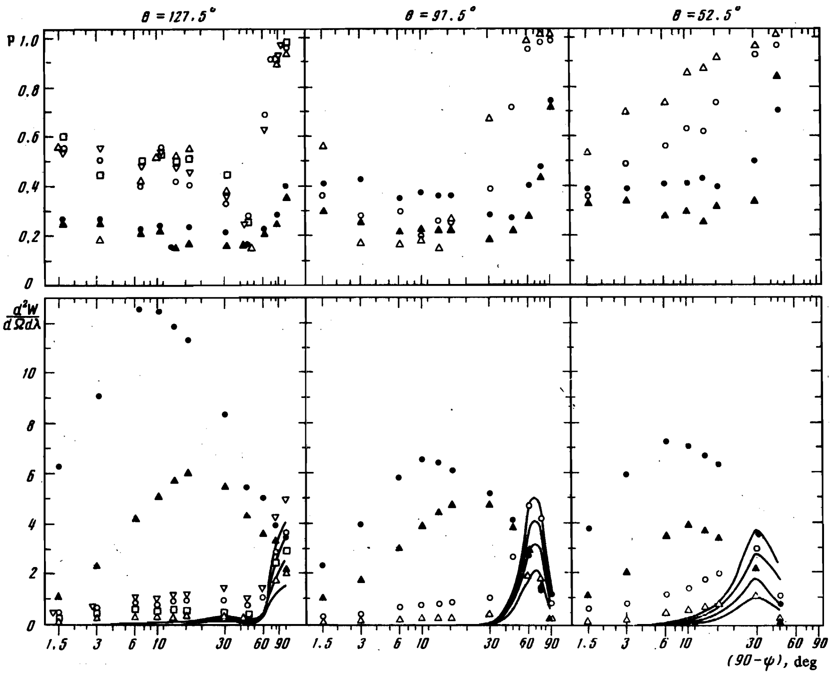

FIG. 4. Energy density of radiation (in units of eV/cm-sr-electron) and degree of polarization as a function of electron entry angle into a target of Ge for various electron energies and observation angles (λ = 5000Å): ▲, △–E = 40 keV, □–E = 60 keV, ●, ○–E = 80 keV, ▽–E = 100 keV. The solid symbols are for R targets and the hollow symbols for P targets.

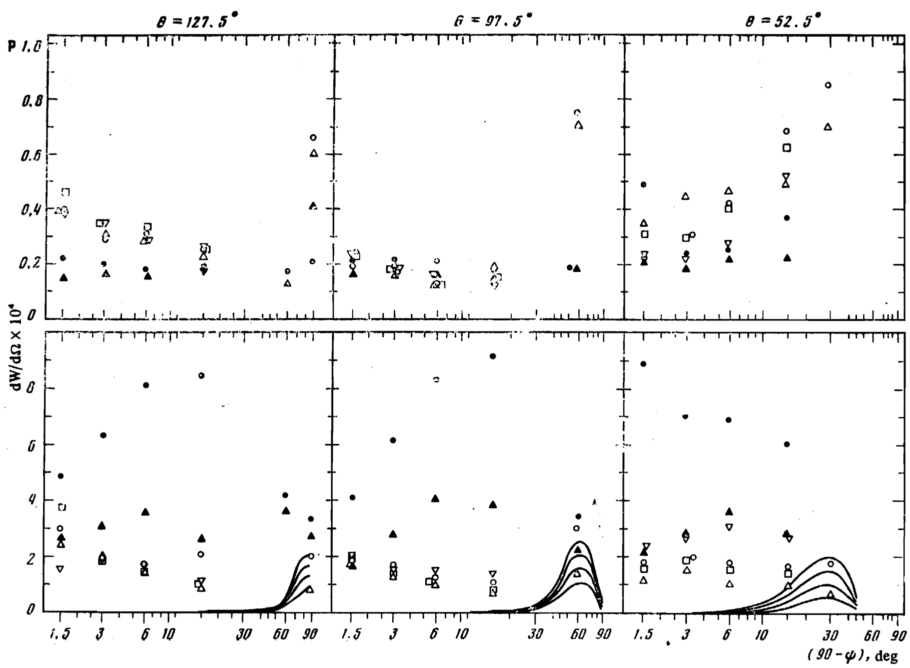

FIG. 5. Total energy of radiation (in units of eV/sr-electron) and degree of polarization as a function of electron entry angle into a target of Ag in the wavelength interval 2800–5800Å: ▲, △–E = 40 keV, □–E = 60 keV, ●, ○–E = 80 keV, ▽–E = 100 keV. The solid points are for R targets and the hollow points are for P targets. The solid curves are theoretical.

Thus, analysis of all data as a whole leads to the conclusion that the luminescence of metals under the action of electrons consists mainly of transition radiation photons and radiation from surface irregularities. Depending on the electron entry direction into the metal and the surface state, one or the other mechanism of radiation production will be dominant.

In conclusion we note that the results of the present experiment provide a basis for believing that detection of radiation emitted by electrons on their entry into the material can serve as a good method for study of the surface. In fact, nonuniformities of height several tens of angstroms excite radiation of sufficient intensity.[16]

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