Bremsstrahlung and Transition Radiation from Ag Foils Bombarded by Non-Normal Incidence Electrons*

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The radiation emitted by self-supporting Ag foils 700 to 1700 Å in thickness was investigated as a function of angle of electron incidence, foil thickness, and degree of polarization. For a foil 700 Å in thickness, the peak at 3300 Å characteristic of transition radiation was found in the emission spectrum when the foil was bombarded by normally incident electrons ($\theta_i=0°$). The wavelength at which the peak appeared increased monotonically with increasing angles of electron incidence until it appeared at $\lambda=3400$ Å for $\theta_i=87°$. For a foil 1680 Å in thickness, the transition radiation peak at $\lambda=3300$ Å was found to decrease in intensity as θ_i increased from normal incidence and finally disappeared at $\theta_i=80°$. For $\theta_i>75°$, another peak appeared at 3500 Å, which increased in intensity for $\theta_i>85°$, and finally became an intense peak at $\lambda=3600$ Å, for $\theta_i=89°$. The dependence of the peak at 3500–3600 Å for large angles of electron incidence on θ_i, electron energy, and polarization agrees with details predicted by a model due to Howe and Ritchie based upon the production of bremsstrahlung in a semi-infinite slab, and leads to the conclusion that the optical emission observed from Ag foils bombarded by grazing-incidence electrons is bremsstrahlung, and not radiation from the decay of surface plasmons, as hypothesized by Boersch *et al.*

INTRODUCTION

THE recent investigation of plasma radiation by Boersch *et al.*[1] revealed a peak in the emission spectrum of silver which was ascribed to the decay of surface plasmons. Using 30-keV electrons at grazing incidence on thick silver foils, Boersch reported a narrow intensity peak at 3500 Å which was more than ten times as great as the previously observed peak at 3300 Å in the transition radiation spectrum for normal-incidence electrons. Because of the dependence of the photon intensity on angle of electron incidence, surface conditions, and the wavelength of peak emission, the emission was attributed to the decay of surface plasma oscillations in the target. The optical emission from Ag foils bombarded by normal-incidence electrons has been studied in great detail by several investigators[2,3] and definitely identified as transition radiation on the basis of its polarization, spectral distribution, and its dependence on foil thickness, electron energy, and angle of observation. The dependence of the radiation intensity on these parameters was calculated by Ritchie and Eldridge[4] on the basis of earlier work by Frank and Ginsburg,[5] who showed that electromagnetic radiation would be emitted whenever a charged particle passes from one medium to another having different optical properties; hence the name "transition radiation."

For grazing incidence electrons, however, the intensity of transition radiation is expected to be quite weak since the normal component of the induced polarization is nearly zero. In addition, although the induced polarization along the foil surface is large, no emission is predicted from a plane surface since the phase velocity of this component (surface plasmons) can never exceed the velocity of light.[6]

In a recent theoretical determination by Howe and Ritchie[7] the intensity distribution of photons emitted from a slab (infinitely thick to photons) irradiated with electrons at arbitrary angles was calculated. Contributions to the spectra were identified as being from transition radiation, bremsstrahlung, and interference effects between these two types of radiation.

In a previous study by Jones *et al.*,[8] identical conditions to those used by Boersch were employed and the results showed the yield of photons to be proportional to the electron beam energy between 40 and 80 keV, a much greater yield for electrons at grazing incidence than for normal incidence, and films unexposed to air producing higher photon yields than those evaporated outside of the target chamber. Although the results as obtained by Jones *et al.*, were in good agreement with the results obtained by Boersch *et al.*, they are not conclusive and leave the positive identification of surface plasma radiation in question. Therefore, a study of the dependence of the emission spectrum on foil thickness, incident electron energy, and polarization of the emitted light was undertaken to provide further information about the observed emission from silver foils bombarded by grazing-incidence electrons.

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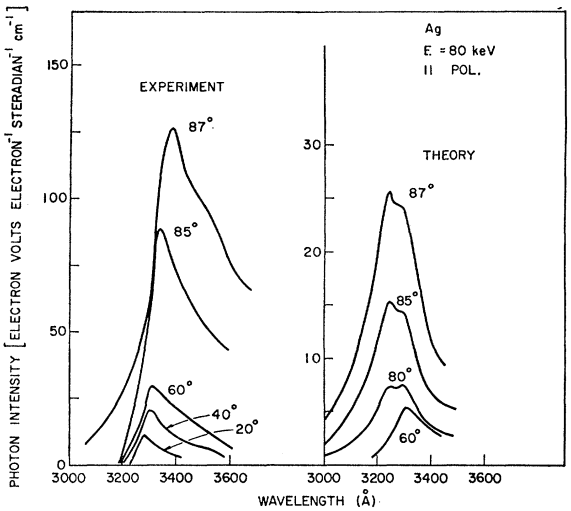

FIG. 1. Spectra of light emitted in the parallel plane of polarization from thin (t=700 Å) self-supporting Ag foils bombarded by 80-keV electrons at various angles of incidence.

EXPERIMENTAL

The experimental arrangement is the same as that described previously.[2] Thin foils were irradiated with 40- to 80-keV electrons from an electron accelerator. The light emitted by these foils at 30° from the foil normal was analyzed with a Seya-Namioka vacuum-ultraviolet spectrometer equipped with a Glan prism polarizer in the exit arm. The polarizer was oriented such that the light polarized either in the plane of incidence (parallel component) or perpendicular to it (perpendicular component) could be detected. The detector was an EMI 6256B quartz-window photomultiplier. Self-supporting Ag foils of thickness 700 to 1700 Å were prepared in a vacuum evaporator. These foils were made by evaporating Ag onto microscope slides previously coated with a wetting agent. The thin foil was then floated off the glass slide and mounted on an aluminum ring which was placed in the target position. Other Ag foils of varying thicknesses were prepared directly in the irradiation chamber by evaporation onto thin Formvar[9] backings to avoid atmospheric contamination. Little difference in spectra was observed between self-supporting foils and foils backed with Formvar. The results presented in this report are for self-supporting foils.

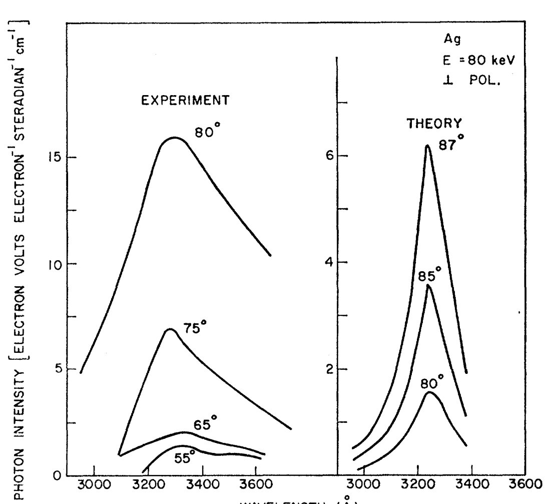

FIG. 2. Spectra of light emitted in the perpendicular plane of polarization from thin (t=700 Å) self-supporting Ag foils bombarded by 80-keV electrons at various angles of incidence.

The emission spectra, whose ordinates are given in units of energy per unit solid angle per cm of wavelength per incident electron, were corrected for the spectral response of the spectrometer and for the area of the foil which is not "seen" by the spectrometer at large angles of electron incidence. The latter correction was determined as follows. The image of a horizontal ribbon filament was focussed at the foil position. By varying the width of the image and observing the light detected by the photomultiplier, the maximum source width that the spectrometer can detect without loss was determined. This width corresponded to the image formed on the foil by the electron beam at an incidence angle of 60°. Therefore, no correction was needed for angles less than 60°, since in this case all the light was detected. For angles greater than 60°, the photon intensity was multiplied by $\cos 60°/\cos\theta_i$. The response of the spectrometer was determined with a tungsten filament lamp calibrated by the National Bureau of Standards. Four separate evaporations were required in order to obtain the data presented. Figures 1 and 2 are from evaporation number 1; Figs. 3 and 4, number 2; Fig. 5, number 3; Figs. 6 and 7, number 4. As a result of slight differences in the foils from different evaporations, only spectra from foils made from the same evaporation can be compared on an absolute intensity basis.

RESULTS AND DISCUSSION

The parallel component of experimental spectra between $\lambda=3100$ Å and 3600 Å for a self-supporting Ag foil 700 Å in thickness, bombarded by electrons with various angles of incidence is shown in Fig. 1 along with the theoretical results of Howe and Ritchie. Although the calculations of Howe and Ritchie are for a semi-infinite slab and do not include large angle multiple scattering of electrons, and thus are not strictly applicable to the present results, a reasonable comparison can be made because the photon attenuation length $\lambda/(4\pi k)$ is 480 Å at $\lambda=3300$ Å.[10] The peak at 3300 Å, characteristic of transition radiation, was found in the emission spectrum when the foil was bombarded by normally incident electrons ($\theta_i=0°$). The wave-length

[9] Obtained from the Shawinigan Products Corporation, New York, New York.

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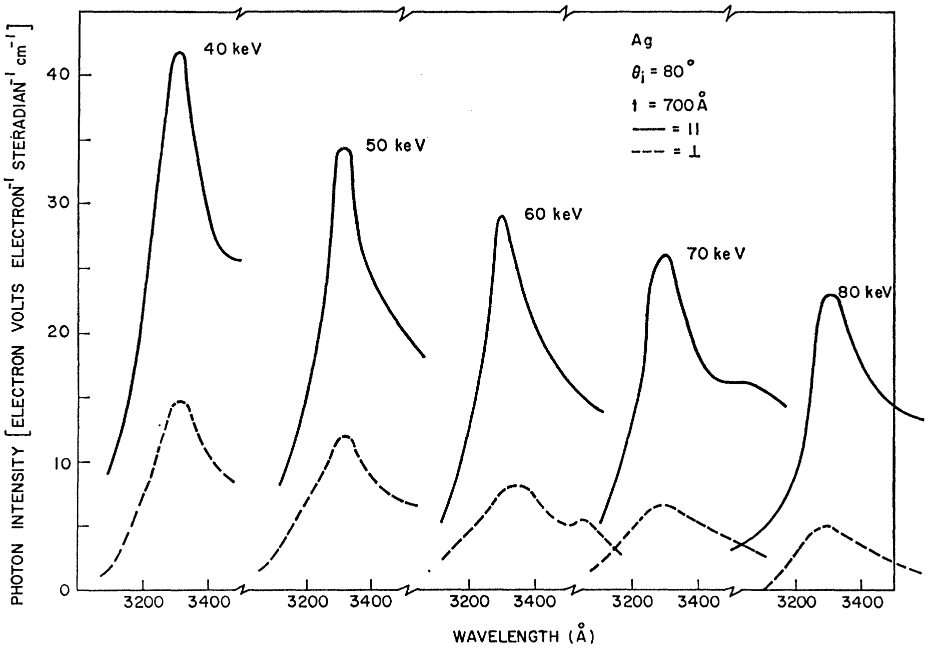

FIG. 3. Spectra of light emitted in the parallel and perpendicular plane of polarization from thin ($t=700$ Å) self-supporting Ag foils bombarded by 40- to 80-keV electrons at 80°.

at which the peak appeared increased monotonically until it appeared at $\lambda=3400$ Å for $\theta_i=87°$. No peak was found at $\lambda=3500$ Å for this foil.

As the angle of electron incidence approaches grazing angles ($\theta_i>80°$) there is a strong peaking of the photon intensity at approximately $\lambda=3400$ Å which conforms to the $(\cos\theta_i)^{-1}$ dependence of bremsstrahlung and is in good agreement with the theory of Howe and Ritchie for non-normal electron incidence. This is because more scatters will occur close to the surface of the foils than in the case of normal incidence, resulting in a larger number of photons escaping from the foil. Both the parallel and perpendicular components show the $(\cos\theta_i)^{-1}$ dependence (Figs. 1 and 2). The spectra from a Ag foil 700 Å in thickness bombarded by 40- to 80-keV electrons at $\theta_i=80°$ are shown in Fig. 3. Both parallel and perpendicular components are seen to decrease in intensity with increasing electron energies.

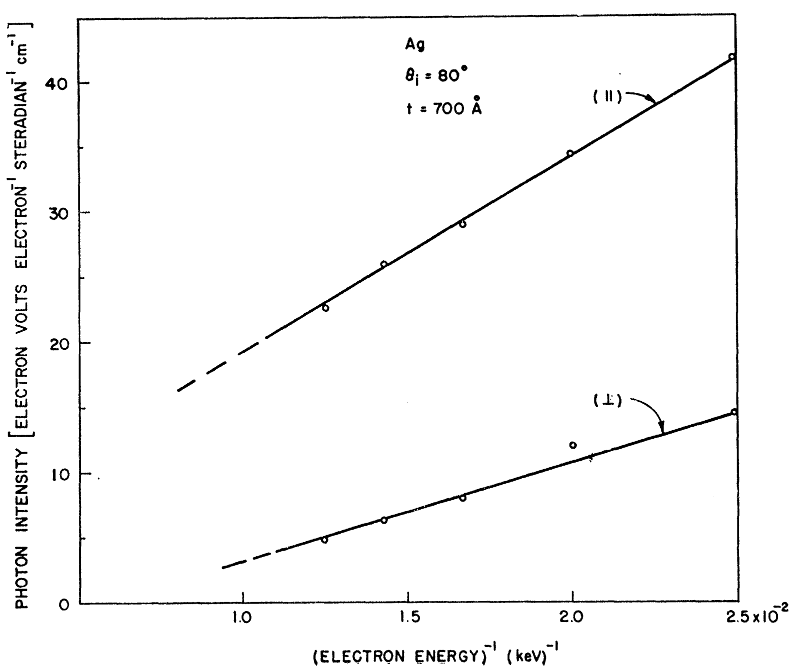

FIG. 4. Peak photon intensity as a function of (electron energy)$^{-1}$ for the parallel and perpendicular polarization components. The angle of electron incidence is 80°.

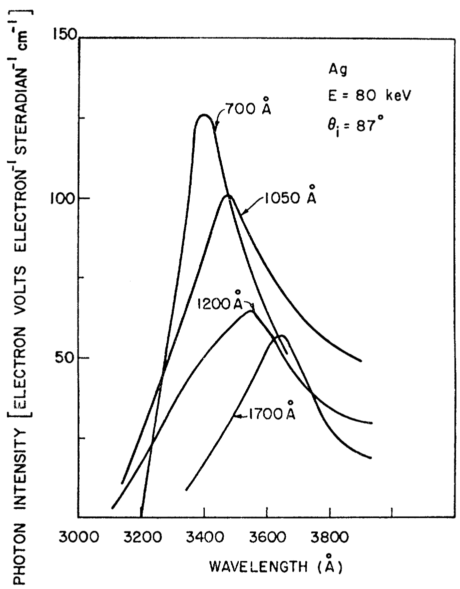

FIG. 5. Photon intensity for silver foils 700, 1050, 1200, and 1700 Å in thickness. The angle of electron incidence is 87°.

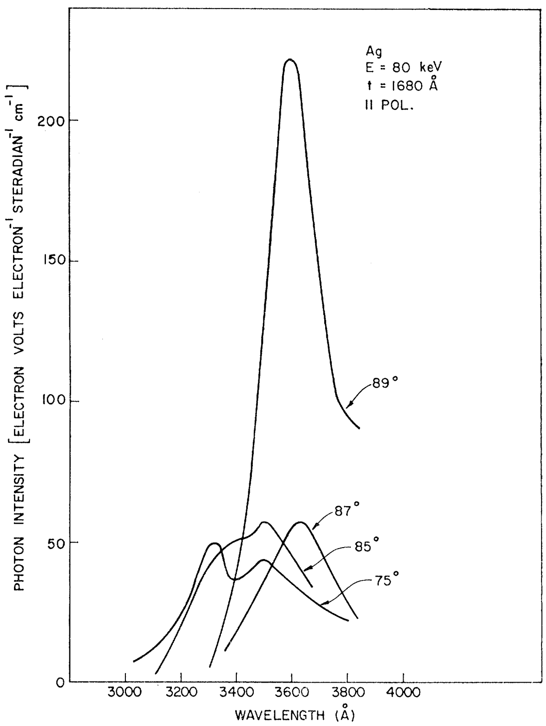

FIG. 6. Spectra of light emitted in the parallel plane of polarization from thick ($t=1680$ Å) self-supporting Ag foils bombarded by 80-keV electrons at various angles of incidence.

The energy dependence of bremsstrahlung production[7,11,12] is proportional approximately to $(1-\beta^2)/\beta^2$, and in terms of the rest mass energy E_0 and the kinetic energy E of the incident electron, is given by $E_0^2/E(E+2E_0)$. For $E<80$ keV, the cross section for bremsstrahlung production is nearly proportional to $1/E$. The photon intensity at the peak wavelength is therefore plotted as a function of $1/E$ in Fig. 4. The perpendicular component is seen to obey the $1/E$ dependence quite well and is, therefore, thought to be comprised of bremsstrahlung alone. The parallel component similarly follows a $1/E$ dependence but in addition is underlaid with a constant term. The parallel component is therefore believed to be comprised primarily of bremsstrahlung, which is responsible for the $1/E$ dependence, with a slight admixture of transition radiation.

The ratio of the parallel to the perpendicular polarization at the peak photon intensity in Fig. 4 is 4.5 at 80 keV, in excellent agreement with the ratio 4.6 calculated by Howe and Ritchie. The experimental and theoretical ratios do not agree as well at the lower energies. At these energies, however, the mean-square electron scattering angle (on which the model is based) is less precisely known. The difference in the intensities of the parallel and perpendicular components results from the polarization effect on the bremsstrahlung photons by transmission into the vacuum at the foil-vacuum interface.

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The experimental spectra from Ag foils 700 to 1700 Å in thickness bombarded by 80 keV electrons at 87° incidence are shown in Fig. 5. It is seen that increasing the foil thickness results in a decrease of the photon intensity and a gradual shift in the wavelength of maximum emission from $\lambda=3400$ to 3600 Å. The decrease in intensity for increasing foil thicknesses is similar to earlier observations at 30° from the foil normal using normal-incidence electrons[3] and has been explained by the increased absorption encountered by the photons in traversing the thicker foils. The shift in the wavelength of peak emission results from the broadening of the sharp peak seen for thin foils.

The spectra for self-supporting Ag foils 1700 Å in thickness are shown in Fig. 6. An intense peak was observed at 3600 Å for angles of electron incidence near 90° similar to that seen by others for thick films.[1,8] To accurately determine the angle of electron-beam incidence, the spectrum was recorded at one degree intervals for $\theta_i>85°$. When the foil was rotated parallel to the electron beam ($\theta_i=90°$) the characteristic spectra could no longer be observed. In this way the angle θ_i was determined to within one degree. The transition radiation peak at 3300 Å, still noticeable at $\theta_i=75°$, gradually disappears for the larger angles of electron incidence. Another peak, which is thought to be bremsstrahlung, begins to appear at $\lambda=3500$ Å for $\theta_i=75°$, and increases in intensity for $\theta_i>85°$, until it becomes quite intense for $\theta_i=89°$.

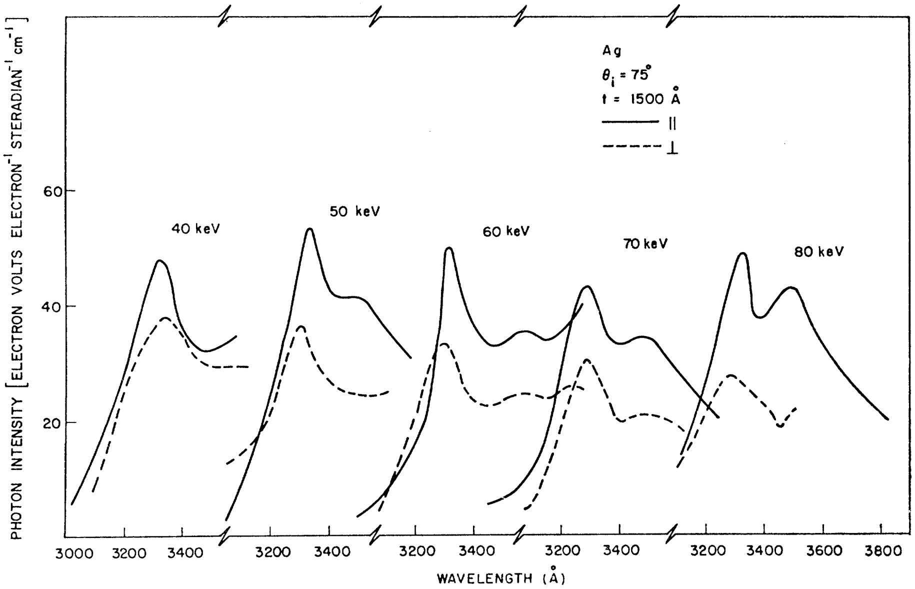

FIG. 7. Spectra of light emitted in the parallel and perpendicular plane of polarization from thick ($t=1500$ Å) self-supporting Ag films bombarded by 40- to 80-keV electrons at 75°.

Figure 7 shows the parallel and perpendicular components of the spectra from a foil 1500 Å in thickness as a function of electron energies for $\theta_i=75°$. The intensity of the parallel component is almost independent of electron energy whereas the perpendicular component is inversely proportional to electron energy. A $1/E$ dependence characteristic of bremsstrahlung is expected in the perpendicular plane since transition radiation is not emitted in this plane. The relatively stable photon intensities in the parallel plane for electron energies 40- to 80-keV can be explained as follows. At this angle of electron incidence ($\theta_i=75°$), the spectrum consists of both transition radiation and bremsstrahlung. At the lower energies, we may conclude that a strong bremsstrahlung component is present in view of the $1/E$ dependence. At the higher energies, transition radiation has increased in intensity and is dominant in the spectrum.

CONCLUSIONS

Silver foils 700 to 1700 Å in thickness bombarded by grazing-incidence electrons ($\theta_i > 80°$) show a peak in the emission spectra at 3400–3600 Å which cannot be accounted for by transition-radiation theory. The present results support the identification of this emission as bremsstrahlung. The peak in the optical emission spectrum was found to agree with the expected $1/E$ dependence between 40- and 80-keV and the $1/\cos\theta_i$ dependence predicted by the theory of Howe and Ritchie for bremsstrahlung. The ratio of the parallel to perpendicular polarized component for $\theta_i=80°$ (4.5 at 80 keV) was found to agree with the ratio predicted theoretically (4.6). The discrepancy between theory and experiment for the wavelength of peak emission remains unexplained.

On the basis of the present results, we conclude that the optical emission observed when silver foils are bombarded by grazing-incidence electrons is from bremstrahlung and is not due to the decay of surface plasmons.

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