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CATHODOLUMINESCENCE OF RUBY AS A FUNCTION OF ANGLE OF INCIDENCE

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The effect is explained in terms of an increase in efficiency with angle of incidence. Inclined excitation is proposed as a method of preventing charging of the surface.

The efficiency η is the ratio of the light energy emitted to the energy of the electron beam [1]; it is dependent on the type of material, input energy, and conditions of use. Here we report results for ruby [2, 3], which have been obtained because some devices use oblique incidence. The emission is shown to be related to the electrical properties, since the material is an insulator and tends to become strongly charged in the beam.

Methods. A PRS apparatus [4] was used with a special attachment allowing the angle of incidence to be varied and the emission to be examined as a function of direction. The PM tube was fitted with a filter to isolate the R line.

Figure 1 gives a general view of the apparatus, with the attachment replacing the upper cover of the measuring chamber. Ten quartz windows at intervals of 9° were located in two mutually perpendicular planes, one of which was the plane of excitation. The electron gun was at a fixed angle of 45° to the plane of the cover, the angle of incidence being varied by rotating the specimen, which altered the position of the normal relative to any given position of the photomultiplier. Correct adjustment was verified from the reflection of light by MgO, which obeys Lambert's law closely.

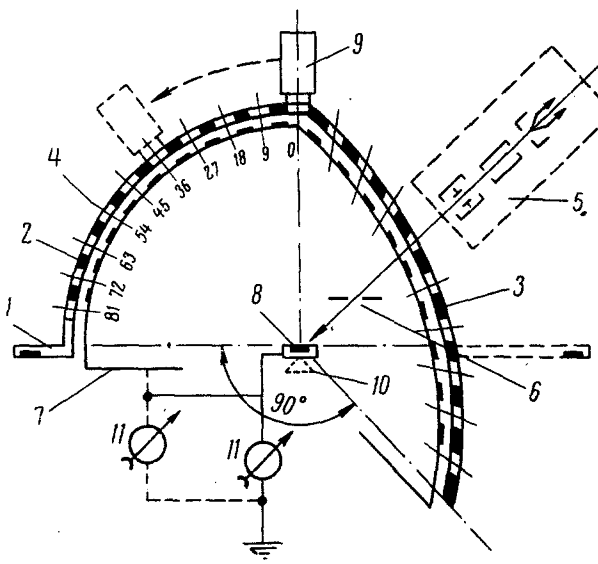

Fig. 1. Apparatus (schematic): 1) cover; 2) and 3) sectors for observing emission: 4) window; 5) electron gun; 6) stop; 7) secondary-electron collector; 8) specimen; 9) PM tube; 10) stops for rotation of specimen; 11) microammeters.

The gun was that used in the PRS apparatus; the accelerating potential was varied from 5 to 20 kV, and the current density from 10^{-6} to 10^{-4} A/cm^2. The beam was stopped down to produce a spot 6 mm in diameter for an angle of incidence α of 45°; rotation of the specimen produced some change in shape, but this did not fall outside the specimen within the limits of α used (0 to 60°).

The attachment records the total beam current i_0, which is the sum of the current i_1 to the specimen and the secondary-emission current i_2. In certain cases these two components were measured separately.

Results and discussion. The $\eta(\alpha)$ relation is deduced from the angular distribution of the emission; the latter should be independent of α. Ruby crystals deviate from Lambert's law by not more than 10–15%; Zn_2SiO_4–Mn (polycrystalline) obeys Lambert's law closely, whereas vacuum-deposited Zn_2SiO_4–Mn gives a dependence intermediate between

Lambert's and Lommel's laws.* These results agree with Ivanov's [5] for photoluminescence. Ruby gives an angular distribution independent of α, so $\eta(\alpha)$ may be deduced from the intensity along the normal (Fig. 2a). There is a steady rise in η for α between 0 and 65°; the maximum η (at ~65°) was taken as 100%. The fall in η for α of 70–90° is due to defocussing and marked reduction in the current reaching the specimen. Considerable error may occur in applying a correction for this effect, so the variation in η is discussed only for α from 0 to 65°. The results of Fig. 2a are for $V = 10$ kV, $j = 4 \times 10^{-5}$ A/cm^2.

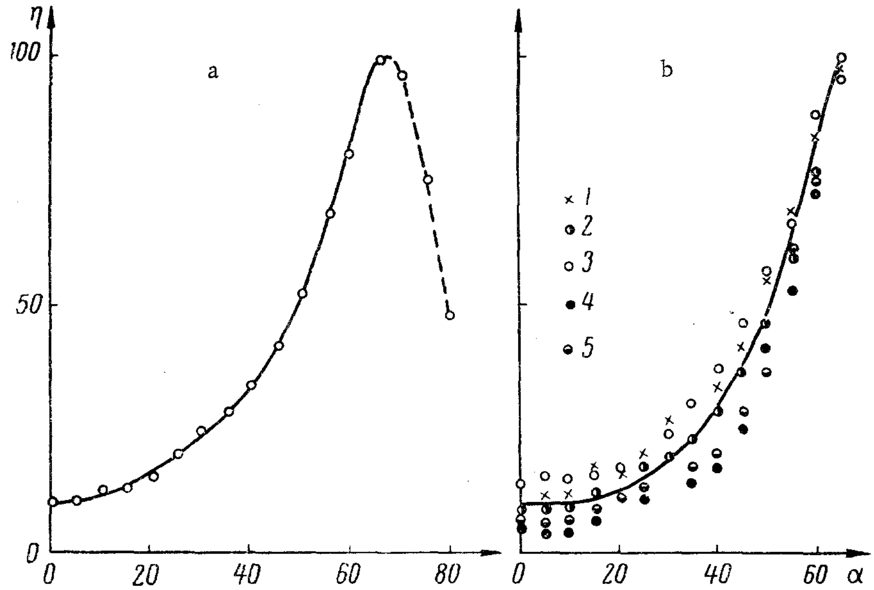

Fig. 2. Efficiency η (%) as a function of α: a) $V = 10$ kV; $j = 4 \times 10^{-5}$ A/cm^2; b) crystal with 0.5% Cr^{3+}; 1) 10 kV and 2×10^{-5} A/cm^2; 2) 10 kV, 10^{-4} A/cm^2; 3) 20 kV, 10^{-4} A/cm^2; crystal with 0.05% Cr^{3+} at 10 kV and 10^{-4} A/cm^2 cut; 4) parallel to optic axis; 5) perpendicular to axis.

Similar trends were obtained for other excitation conditions. There were small effects from the Cr^{3+} content and the cutting of the crystal (Fig. 2b). At high j the ratio of the η for 65 and 0° was 10.

This increase in η with α is due to the low conductivity; the crystal becomes charged. In the steady state, i_0 is the sum of i_1 and i_2, balance being attained by the retarding action of the space charge, which produces

$$\sigma(V_0 - \Delta V) + i_1/i_0 = 1,$$

in which σ is the secondary-emission factor, V_0 is the applied potential difference, and ΔV is the potential due to the charge on the crystal; σ increases with α for most polished materials [6], so we would expect ΔV to be inversely related to α. Separate measurement of i_1 and i_2 showed that this does occur. The change in the current distribution is dependent on the excitation conditions; Fig. 3 illustrates this for $V = 10$ kV and $j = 6 \times 10^{-5}$ A/cm^2, the ratio of the η corresponding roughly to the ratio of the currents:

$$\frac{\eta(\alpha)}{\eta(\alpha=0)} \approx \frac{i_2(\alpha)}{i_1(\alpha)} : \frac{i_2(0)}{i_1(0)}.$$

This effect is one cause of saturation in cathodoluminescence. Figure 4 illustrates the effect on the intensity as a function of j for three α; saturation occurs for $\alpha = 0$ in the range 10^{-5} to 10^{-4} A/cm^2, whereas for $\alpha = 65°$ a rectilinear relation applies over this range, so there is neither thermal quenching nor saturation of the Cr^{3+} centers [2]. Hence oblique excitation of a screen may be used to suppress charging effects in studies on the fall in η at high j.

Aluminizing removes the charge, but it does not allow one to extract the light from the side of incidence. Measurements in transmission on ruby (done with the lower gun of the PRS) showed that η is not a function of α for an aluminized crystal, whereas the maximum η (at $\alpha = 65°$) for a crystal without Al was roughly as for an aluminized crystal. Hence oblique excitation may be used in various practical applications.

* The difference in these distributions causes the observed η for the film to be reduced by 25–30%.

Conclusions

1. The angular distribution of the emission from a ruby crystal fits Lambert's law more closely than Lommel's law and is independent of the angle of incidence.

2. The increase in η with α is due to reduced space charge, which is accounted for by the angular dependence of the secondary emission.

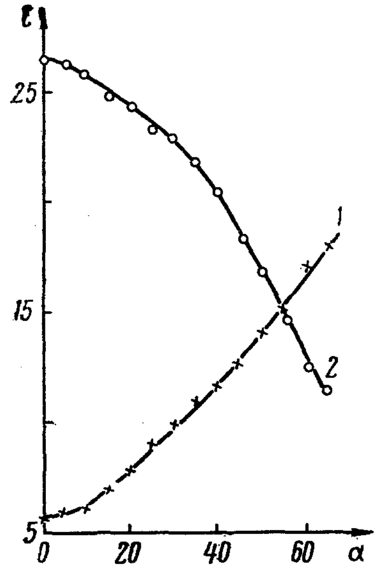

Fig. 3. Currents: 1) i_2; 2) i_1 as functions of α.

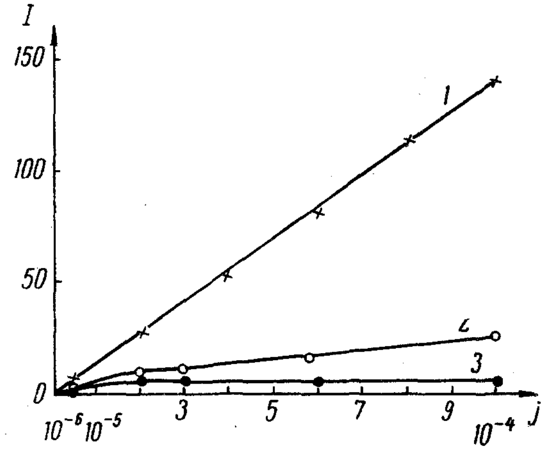

Fig. 4. Intensity I (relative) as a function of current density j (A/cm^2) for α of: 1) 65° C; 2) 45° C; 3) 0.

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