Investigation of the Angular and Energy Distributions of Secondary Electrons from Cuprous Oxide

N. B. GORNYI

(Submitted to JETP editor June 24, 1955)
J. Exptl.Theoret. Phys. (U.S.S.R.) 31, 386-92 (September, 1956)

The angular distribution of secondary electrons was investigated using a vacuum system containing a spherical collector whose surface was divided into several conducting belts. The observed angular distributions of the secondary electrons exhibit pronounced maxima at large angles (~ 60°). It is shown that the observed distributions are distorted from the true distributions by secondary emission from the collector (tertiary electrons). A method to correct for this effect is introduced. The corrected angular distributions obey a cosine law. The energy distributions for the different angles of emission of the secondary electrons are investigated by the method of electrical differentiation.

INTRODUCTION

THE investigation of the angular and energy distributions of secondary electrons is not only interesting from the point of view of applications but it also is important in explaining the mechanism of secondary electron emission. The different theories of secondary emission[1,2] give different angular distributions. According to Viatskin's theory[2] the electrons come out mainly at large angles ($\varphi \sim 65°$) with respect to the incoming electron direction in the case of normal incidence of the primaries. On the other hand, in the theory of Kadyshevich[1] the number of secondaries increases with decreasing angle φ. It has been shown in several investigations[3] that the yield of secondary electrons j (number of secondary electrons per steradian) decreases with increasing angle between the normal and the direction of emission. Kushnir and Frumin[4] have found for Mo and Ag that in normal incidence of the primary electrons, the secondary emission j first decreases with increasing angle φ; from a certain angle on, j begins to increase and reaches a maximum at an angle $\varphi \approx 60°$ to 70°. An investigation of the secondaries from nickel[5] and soot[6], also for normal incidence of the primary electrons, showed that j changes approximately according to cos φ. This is in disagreement with the results of Ref. 4. The main shortcoming of the above investigations seems to be the absence of compensation of the magnetic field of the earth which may greatly influence the trajectories of slow electrons (the radius of curvature of 3 ev electrons at $H \approx 0.5$ Oe is roughly 10 cm).

EXPERIMENTAL ARRANGEMENT

The measurement of the angular distribution of secondary electrons was performed with the following apparatus. The vacuum system had a spherical part with a diameter of 110 mm, the inside of which was painted with aquadag. This served as the collector for the secondary electrons. The collector was separated into five mutually insulated belts. The secondary electrons could reach only the upper four belts, the fifth was the lower half sphere. The areas and the median values of the angle φ for the different belts are: 1. 2cm^2 and 12.5°; 2. 3.2 cm^2 and 24.3°; 3. 5.8 cm^2 and 55.3°; 4. 6.6 cm^2 and 79.5°. The emitter E, consisting of polycrystalline cuprous oxide, was placed in the center of the sphere. The emitter was attached to a cylindrical electrode with a diameter of 20 mm and a length of 17 mm. Inside of it was placed a thermocouple for temperature measurements and a bifilar filament W which served as a heater. The preparation and baking of the system was performed in the way as described in Ref. 7. The pressure in the system as measured by an ionization gauge before sealing off of the system was 10^{-6} cm Hg. After sealing off, a getter was flashed at 450° C. When connecting only one belt to the current measuring setup, the potentials on all belts remained equal. Two coils of 1m. diameter were used to compensate the earth's magnetic field.

RESULTS

Figure 1 shows the resultant curves obtained from each belt separately and from the entire collector. The primary electron energy was $V_p = 400$ v; the temperature of the emitter was 400°. Figure 2 shows the energy distribution of the electrons. This was obtained under the same conditions by the method of electrical differentiation.[7,8] The form of the curves of the current at positive V_k (Fig. 1) and also of the energy distribution (Fig. 2) is quite different for the different belts. The slope of the current collected at belt 1 shows a sharp break at $V_k \approx 0$. For positive, increasing V_k, the value I_2 / I_1 keeps increasing until it saturates at $V_k \approx 20$ V. The curve showing the current to belt 2 also has a

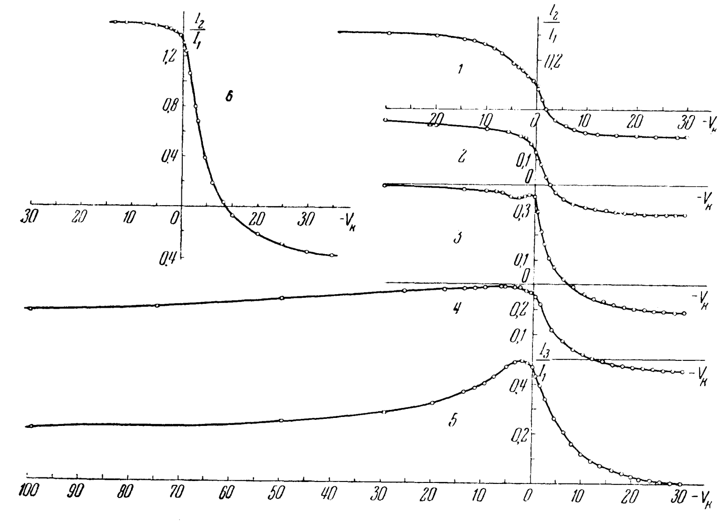

FIG. 1. Currents collected at $V_p = 400$ v and $t = 400°$; curves *1* to *5* for the belts 1 to 5 separately, curve *6* — total current.

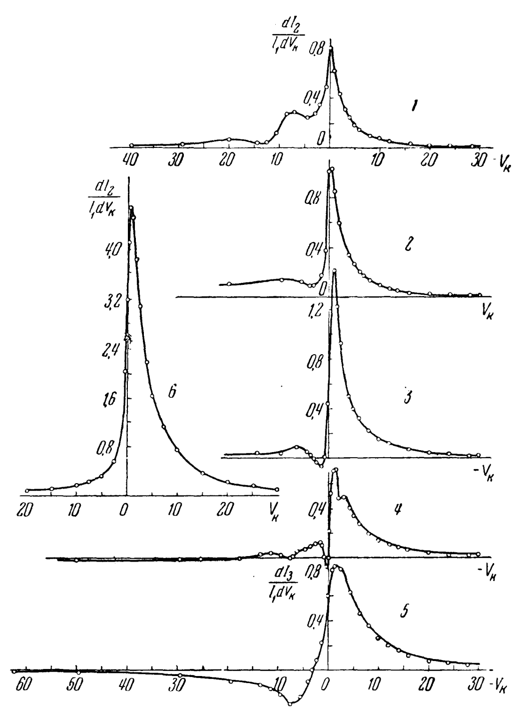

FIG. 2. Energy distributions for $V_p = 400$ v and $t = 400°$; curves *1* to *5* for the belts 1 to 5 separately, curve *6* for the whole collector.

break; it occurs at $V_k \approx 3$ v. At roughly the same voltage the curves of the currents to belts 3 and 4 even have an extremum. The currents to belts 2 and 3 increase monotonically while the currents to belts 4 and 5 decrease for increasing V_k. These collected currents, particularly for belt 5, still show rather marked variation around 30 v and reach saturation only around $V \approx 80$ v

As already mentioned, secondary electrons can not reach region 5 of the collector. Therefore the curve 5, Fig. 1, shows the current of tertiary electrons emitted from the other belts of the collector due to secondary electron impact at different collector potentials. The slight decrease of the values of this current for increasing positive V_k is due to a bending of the trajectories of the tertiary electrons by the electric field which deflects some of the electrons away from region 5 to the other belts. But even at very large positive V_k (100 – 150 v), the number of tertiaries reaching 5 is still roughly one half the value reaching it at $V_k = 0$.

The tertiary electrons emitted by any of the belts arrive not only at 5 but also at the belts 1 to 4. Therefore, the measured currents consist of the arriving secondaries, plus the tertiaries arriving from the other 3 belts, minus the tertiaries emitted by the belt under consideration and collected by the other belts and the emitter electrode. One must then reckon with the fact that the collected secondary currents to the different belts will be distorted for all values of V_k (even for large positive ones) by tertiary currents. The amount of distortion will be different for the different belts.

There was another source of errors in our setup. The secondary electrons striking the unpainted strips of glass (width 1mm) between the belts could charge up this surface, thus creating local electric fields. However it was possible to check on the existence of such fields by sudden changes in

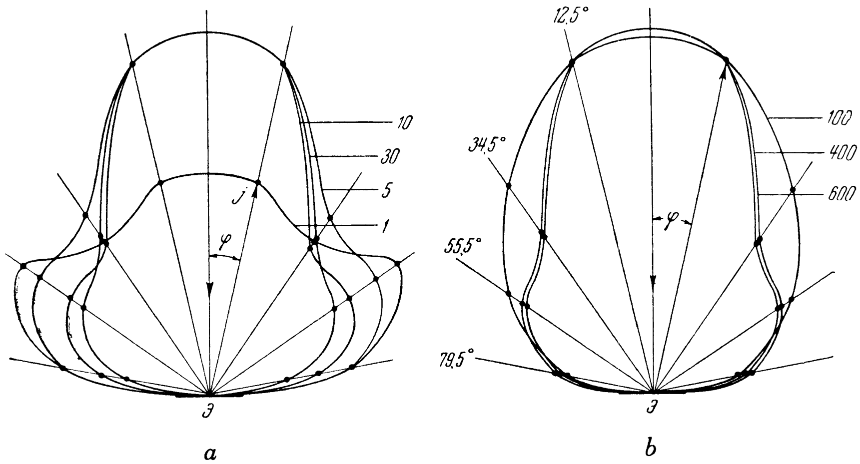

FIG. 3. Angular distributions at the following conditions: *a*. V_p = 400 v, V_k = 1, 5, 10 and 30 v; *b*. V_p = 100, 400, and 600 v, V_k = 30 v.

V_k. It turned out that the glass surfaces were essentially uncharged for positive, zero, and even for slightly negative V_k. This clearly can be explained in the following way. There are both fast electrons striking the collector for which the coefficient of secondary emission on glass, δ_1, is larger than 1, and slow electrons with a coefficient δ_2 smaller than 1. The fast ones would charge the glass positively, the slow ones negatively. Thus, under favorable ratios of fast to slow electrons as well as of δ_1 to δ_2, the glass surface will not become charged.

Figures 3 and 4 show the angular distributions as obtained in this experiment. (j is the current per steradian, φ—the angle to the normal). Except for curve *a*, Fig. 3, the different curves are normalized to coincide at φ= 12.5°. Curve *a*, Fig. 3, shows a pronounced maximum at $\varphi \approx 55°$ in addition to the high value of j at small angles This results in agreement with results of Ref. 4. However, with increasing positive values of V_k, the angular distributions become smoother by an increase of j at small angles (φ= 12.5° and 35.5°) and a decrease at φ= 79.5°(see Fig. 1). At larger values of V_k, the distortions due to secondaries are somewhat smaller, due to the fact that more of them return to the belt from which they were emitted. Therefore, the angular distributions obtained for large positive V_k are closer to the actual values. The large values of j at large φ(55.3° and 79.5°) obtained here for small V_k (as well as in Ref. 4) are due to the larger distortions introduced by the tertiaries. For smaller primary electron energies (V_p = 100 v.), there should be emitted fewer tertiaries and therefore the distortions due to them should be smaller. Indeed as can be seen in Fig. 3b, the curves for V_p = 400 v and 600 v have a pronounced bump at 55° due to tertiaries which is absent from the curve for V_p = 100 v.

CORRECTION OF THE DISTORTIONS INTRODUCED BY TERTIARY ELECTRONS

In order to obtain the true angular distributions, one has to correct the experimental results for the influence of the tertiaries. It is advantageous to correct the results obtained at V_k = 0 since then the trajectories of the secondaries as well as the tertiaries will be straight lines and the electrons will keep the direction of their emission.

The procedure to obtain the corrections is as follows. The current of the tertiaries from the belts 1 to 4 reaching the region 5 is known. From the knowledge of the geometry of the apparatus— the areas of the belts and the solid angles with which the different belts see each other and the emitter electrode— it is possible to obtain the values of the tertiaries arriving from each of the belts at the region 5 and at the other belts and at the electrode containing the emitter. The corrected value of the secondary current reaching each belt can now be obtained by adding to the measured current the tertiary currents leaving the belt under consideration and subtracting the tertiary currents arriving from the other belts.

In order to obtain the different tertiary currents one needs to know the angular distribution of the emitted tertiaries. As pointed out earlier, the high values of j at large φ are due to tertiary electrons. One therefore can assume that the secondary emission increases monotonically with decreasing

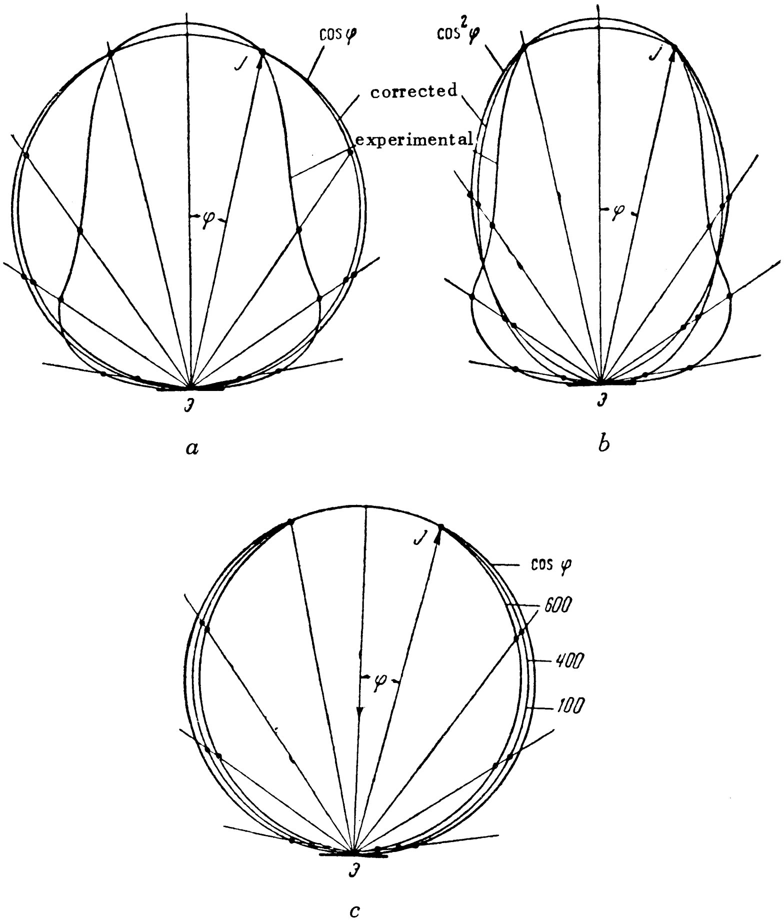

FIG. 4. Corrected angular distributions: *a*. assumed distribution ~ cos φ; *b*. assumed distribution ~ cos^2 φ (V_p = 400 v, V_k = 30 v for both *a* and *b*); *c*. assumed distribution ~ cos φ, V_p = 100, 400, and 600 v.

angle φ (see Fig. 3, b). A natural choice for the angular distribution seems to be a dependence according to a power of cos φ. After applying the corrections, the distortions introduced by the tertiaries should disappear and the obtained angular distribution of the secondary emission should then coincide with the assumed distribution.

DISCUSSION OF THE OBTAINED RESULTS

1. In Fig. 4a there is shown the corrected angular distribution with corrections according to a cos φ dependence, while in Fig. 4b, a dependence according to cos^2 φ was chosen. It turned out that these powers of cos φ resulted in corrected curves closest to the assumed dependence (viz. cos φ or cos^2 φ respectively). As already mentioned the distortions introduced by the tertiaries decrease with increasing V_k. Therefore, the character of the curves of Fig. 1 indicates the sign of the corrections for the different belts. Thus the correction for belt 4 should decrease the measured value of j, since I_2 / I_1 decreases with increasing V_k (Fig. 1, curve 4). This is the case both for the cos φ and the cos^2 φ distribution (Fig. 4a and b). Similarly, the correction for belt 3 should increase the measured value of j in accordance with curve 3, Fig. 1. However this is the case only for the distribution cos φ (Fig. 4a) and not for cos^2 φ (Fig. 4b). Therefore one has to conclude that the angular distribution of secondary electrons emitted from cuprous oxide has the form cos φ.

Fig. 4c shows the angular distributions obtained with primary electron energies of 100, 400, and 600 v. The angular distributions for 100 and 400 v are almost identical while the one for 600 v is slightly narrower, indicating a decrease of emission at large angles.

2. We now shall discuss the results obtained on the energy distribution of secondary electrons for the different directions of emission. In the region of positive V_k the curves for the energy distributions (see Fig. 2) are distorted for the following reasons: as V_k decreases, (*i*) the number of tertiary electrons surmounting the retarding field and reaching the electrode with the emitter increases; (*ii*) the number of tertiary electrons arriving from the other belts increases. The first effect decreases, and the second increases, the values of the measured currents. The relative number of tertiaries leaving the first belt is considerably larger than the number of tertiaries arriving. Therefore, the distortions for this belt are larger, as is borne out by our results (Fig. 2).

The value of the total current from the collector (Fig. 1, curve *6*) is not constant for different positive V_k but decreases markedly with decreasing V_k, beginning at approximately 10 v. Accordingly, the curve showing the energy distribution of the electrons reaching the collector (Fig. 2, curve *6*) in this same region shows a large value. This decrease of the collected current can be explained by the increased number of tertiaries reaching the emitter electrode due to the decrease of the retarding field associated with the decrease of the positive value of V_k.

In the region of negative V_k there also exist distortions. As V_k becomes more negative, (*i*) the number of tertiaries reaching the electrode *E* decreases because the number of (low energy) secondaries reaching the collector decreases, and (*ii*) more tertiary electrons which were emitted in such directions as to miss the emitter electrode are deflected towards it by the electric field and reach it nevertheless.

The ratios I_2 / I_1 attain negative values starting with a certain small negative V_k (see Fig. 1). This comes about when the number of tertiaries leaving the belt is larger than the number of secondaries arriving at the belt. In our numbering of the belts the ratio of the number of tertiary electrons leaving a belt to that arriving at the belt increases with decrease of the belt number. Therefore the value of V_k at which the ratio I_2 / I_1 becomes negative decreases as one goes from belt 4 to belt 1. (Fig. 1). Negative I_2 / I_1 in the region of negative V_k have been obtained also by other authors (see for example Refs. 9,10), who obtained results corresponding to our curve *6*, Fig. 1.

Curve 5, Fig. 2, shows the "speed" of the decrease of the number of tertiaries reaching belt 5 with increasing negative V_k. To a certain degree, it shows the distortions introduced by tertiary emission in the energy distributions of the secondaries obtained for the four other belts. For a given belt, the number of arriving tertiaries increases and the number of arriving secondaries decreases with increasing φ. For belt 4, the number of arriving tertiaries is greater than the number of arriving secondaries. One therefore should expect rather large distortions here. Indeed, curve 4, Fig. 2 shows a kink at $V_k \sim 3$ v, due to the considered distortions.

The position of the maximum in the curves of the energy distribution is being displaced insignificantly towards higher electron energy with increase of the emission angle of the secondaries. This displacement amounts to roughly 1 v for a change of φ from 12.5° to 79.5.° This is considerably smaller than as observed in Ref. 4, where this displacement was 20 v and larger. It is possible that our small value for the displacement is due to distortions from tertiary electrons which may have a different influence on the energy distributions of the different belts.

I am grateful to L. M. Rakhovich, A. Iu. Reitsakas, V. A. Bolotin and R. S. Breslav, who participated in performing the measurements.

---

[1] A. E. Kadyshevich, J. Exptl. Theoret. Phys. (U.S.S.R.) 9, 930 (1939).

[2] A. Ia. Viatskin, J. Exptl. Theoret. Phys. (U.S.S.R.) 12, 22 (1942).

[3] K. G. McKay, *Secondary Electron Emission*, in *Advances in Electronics*, L. Marton Editor, (Acad. Press Inc., 1948) Vol. 1, p. 65.

[4] Iu. M. Kushnir and M. I. Frumin, J. Techn. Phys. (U.S.S.R.) 11, 317 (1941).

[5] J. H. L. Jonker, Philips Res. Rep. 6, 372 (1951).

[6] J. L. H. Jonker, Philips Res. Rep. 8, 434 (1953).

[7] N. B. Gornyi, J. Exptl. Theoret. Phys. (U.S.S.R.) 27, 171 (1954).

[8] N. B. Gornyi and I. M. Rakhovich, J. Exptl. Theoret. Phys. (U.S.S.R.) 26, 454 (1954).

[9] A. I. Piatnitskii, J. Techn. Phys. (U.S.S.R.) 8, 1014 (1938).

[10] J. B. Johnson and K. G. McKay, Phys. Rev. 91, 582 (1953).

Translated by M. Danos
79