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Electron Emission from Dielectric Films Bombarded by Positive Hydrogen Ions

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An investigation has been made of the electron emission which is produced by bombarding dielectric films with positive ions and which continues after termination of the ion bombardment. The electron emission was excited by hydrogen ions, oxygen ions, and lithium ions. The emission has been observed in films of CaF_2, B_2O_3, Al_2O_3, and in mica sheets. The effect of target temperature on emission was investigated. The potentials at the film surfaces have been measured.

WHEN thin dielectric films deposited on a metal substrate are bombarded by electrons or ions, under certain conditions there is observed an extended electron emission which continues after the bombardment is terminated. The origin of this emission seems to be associated with the positive charge at the surface of the dielectric. Malter [1], who discovered this effect, and other investigators bombarded the surface of a dielectric film with electrons to obtain the emission. Starodubtsev[2] obtained this emission by creating a positive charge at the surface of a B_2O_3 film bombarded by K^+ ions and B_2O^+ ions.

The present work was undertaken to obtain more information on the electron emission from dielectric films, deposited on a metal substrate, which is produced when the films are bombarded by positive ions.

DESCRIPTION OF THE APPARATUS AND METHOD OF MEASUREMENT

The experiments were carried out with the apparatus shown in Fig. 1. The target 6 in the operating chamber 8 is bombarded by positive ions selected by the mass-analyzer 2. The instrument frame is grounded. Ions which leave the mass-analyzer pass through two diaphragms 3 with an aperture diameter of 4 mm. To inhibit secondary-electron emission from diaphragm 3, a negative potential of 300 volts is applied to the cylindrical electrode 4 (inner diameter 12 mm, length 15 mm). The target holder 7, which is insulated from the frame and is in electrical contact with the target 6, can be rotated without breaking the vacuum. The micrometer screw 9 is insulated from the frame and is used to move the probe 10 back and forth without disturbing the vacuum. The probe 10 can touch the target 6, as desired, in which case electrical contact is established between the target and the micrometer screw. It is also possible, without disturbing the vacuum, to position a flat disc-collector (not shown in Fig. 1) between the target and collector 5; this disc-collector is insulated from the frame but is in contact with the collector. The ion current is measured by the galvanometer G in the collector–target circuit when the collector potential $V_c = 0$. The electron emission curve is measured with the same galvanometer G, in the collector–target or disc-collector-target circuit, but with a positive collector potential V_c varying from 0 to 3,000 volts applied to the collector. The dielectric film is deposited on the target by vacuum evaporation in the operating chamber 8 while a vacuum of approximately 10^{-6} mm Hg is maintained. By rotating the rod 7, the targets are set over the evaporator 1, located in the bottom part of the operating chamber 8, and B_2O_3 and CaF_2 are evaporated on to the molybdenum substrate. After the film is evaporated, the target is positioned opposite the collector and subjected to ion bombardment. Before deposition of the film,

the target substrate is heated to 1,000–1,200° C by electron bombardment (the electron–bombardment device is not shown in Fig. 1). The target-substrate heating is carried on until the vacuum in the operating chamber cannot be maintained at 10^{-6} mm Hg. The CaF_2 film was also vacuum evaporated in another chamber with and without substrate baking and then transferred in air to the operating chamber. No noticeable difference in the properties of the targets with the CaF_2 films, prepared in the manner indicated above, was found. The thickness of the film is measured to an accuracy of 1 μ with a multiple –beam interferometer. The targets are bombarded by a beam of positive ions selected by the mass analyzer, with energies ranging from 10 to 40 kev at currents ranging from 2 to 6×10^{-7} amp.

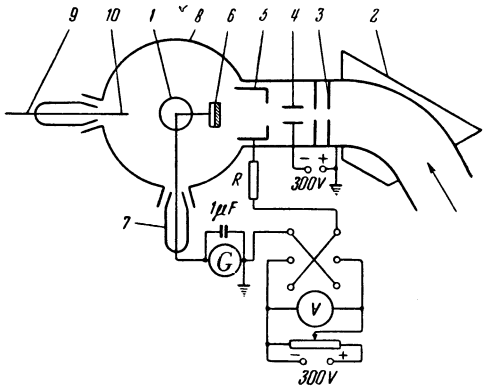

FIG. 1. Diagram of the apparatus.

RESULTS OF THE MEASUREMENTS

Electron Emission from B_2O_3 Films. B_2O_3 was evaporated from a conical tungsten spiral on to the molybdenum substrate. It was found that the vacuum in the operating chamber improved noticeably during intense evaporation of B_2O_3. Following evaporation of the film, the target was heated several times to temperatures of 800–900° C. The thickness of the B_2O_3 film in the experiments being described here varied from 10 to 15 μ. The target was exposed to a beam of protons with an energy of 10 kev.

In Fig. 2 are shown the results of the measurement of electron emission from two targets, I and II, prepared in the same way, and exposed under the same conditions for one minute with $V_c = +400$ volts and an external ballast resistor R = 1500 ohms. The distance between the collector and the target was 10 mm.

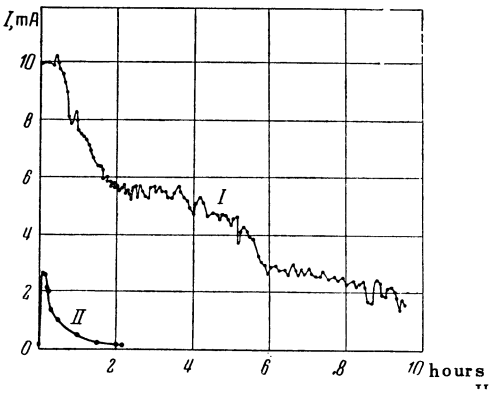

FIG. 2. Electron emission from B_2O_3 films. The time dependence of the emission current I is shown.

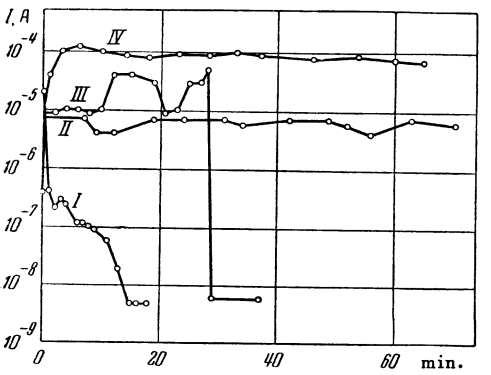

FIG. 3. Electron emission from CaF_2 films. The time dependence for the emission current I is shown for films of various thicknesses: *I*)thickness 20 μ, V_c = 2,500 volts; *II*–thickness 309 μ, V_c = 3,000 volts; *III*–thickness 75 μ, V_c = 2,600 volts; *IV*–thickness 105 μ, V_c = 1,000 volts.

As is apparent from the data, the emission currents from identical films, exposed to a proton beam under identical conditions, vary by a large factor from one experiment to another. Many such experiments were carried out and the curves shown in Fig. 2 are typical.

Electron Emission from Thin Mica Sheets. Thin cleavage sheets of mica (muscovite) with thicknesses ranging from 3 to 70 μ using substrates of aquadag or vacuum–evaporated silver, were bombarded by beams of H_1^+, H_2^+, H_3^+ and O_2^+ ions with energies from 10 to 40 kev for 1–2 min with V_c ranging from 200 to 3,000 volts and R = 1,500 ohms. The distance between the col-

lector and target was 10 mm. After bombardment was terminated, electron emissionwas observed in some of the targets, with V_c set at a fixed value.

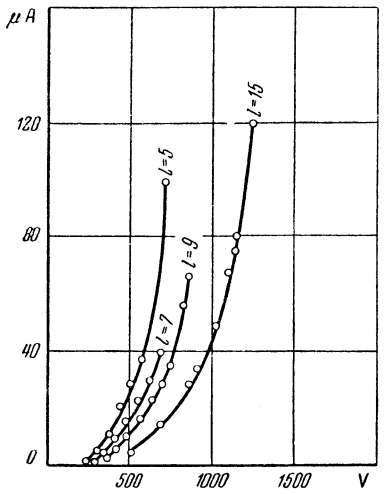

FIG. 4. Electron emission from CaF_2 films. The voltage–current characteristics for the emission are shown for various distances l-between the collector and the target.

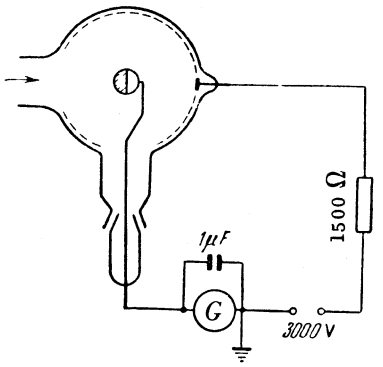

FIG. 5. Diagram of the electron projector.

A total of 118 targets were tested; of these, 29 exhibited electron emission. The emission was observed in sheet thicknesses ranging from 3 to 64 μ, and the highest value of the emission current was 14 μ amp.

In various experiments the time required for the emission to fall from the maxiuum value to the minimum detectable value (10^{-9} amp) varied from several minutes to five hours. It is obvious that one cannot discuss reproducibility of the results. Changing the type of ion or the beam energy, over the region which was investigated, had no effect.

Electron Emission from Al_2O_3 Films. Films of Al_2O_3 were obtained by anodizing polished aluminum in an electrolytic bath (3 percent tartaric acid and ammonium hydroxide, pH = 5.5) for a period of 15 minutes.[3] The thickness of the Al_2O_3 film wasdetermined from the formula

$$t = 13.5\,V,$$

where t is the thickness in Angstroms and V is the voltage in volts.[3] Using this process, transparent non-porous layers of Al_2O_3 with thicknesses from 1.2×10^{-7} to 2.6×10^{-5} cm were obtained on the polished Al.

When these targets were bombarded by beams of H_1^+, H_2^+ and H_3^+ ions with energies from 10 to 40 kev secondary emission was observed. The secondary emission factor was $\sigma \approx 3$. No delayed emission was found in films of this thickness.

TABLE I

Chamber pressure in mm Hg.	Temperature of the container °C.	Cross-sectional resistance, ohms/cm²
760	20	10^5
10^{-5}	20	10^{13}
10^{-5}	60	10^{10}

By passing a current of 1.5 ma for a period of 190 hours to the polished Al in the same electrolytic bath, opaque porous films of Al_2O_3, 5–6 μ in thickness were obtained. The thickness of these films was measured with a multiple-beam interferometer after they were removed from the Al in a $HgCl_2$ solution, washed in distilled water, and dried.

The targets with Al_2O_3 films of the indicated thickness were bombarded with a H_1^+ beam with an energy of 10 kev for 10 seconds with V_c = 2,000 volts and R = 1,500 ohms. Electron emission was observed in these targets after the bombardment was terminated. The emission lasted for 12 min and the largest value of the emission current was 6 μ amp.

Electron Emission from CaF_2 Films. Calcium fluoride was vacuum evaporated from a molybdenum

container on to the molybdenum substrate. Targets with films of CaF_2 with thicknesses from 2 to 309 μ were bombarded by beams of H_1^+, H_2^+, H_3^+ and O_2^+ ions with energies from 10 to 40 kev and Li_7^+ ions with energies from 2 to 3 kev for a period of 20 sec with V_c ranging from 200 to 3,000 volts and R = 1,500 ohms. 30 targets were tested and in all targets electron emission lasted from several minutes to six hours. The highest emission current was 150 μ amp. In Fig. 3, the time dependence of theelectron emission current for targets with CaF_2 films is shown for films of different thicknesses.

In Fig. 4 the voltage-current characteristics of the electron emission are shown for a target with a CaF_2 film 40–45 μ thick with various distances between the collector and the target l, at room temperature. It should be noted that the voltage-current characteristics will have the form shown in Fig. 4 in each target only if the following conditions are fulfilled: 1) the period of time in which the voltage -current characterisitics are taken must be less than one–two hours; 2) the film must not be punctured. Film punctures are produced when the voltage V_c is too high, at high emission currents with small l (1–3 mm) and when thetarget temperature is increased to 70–80° C. When the film is punctured, circular flashes of light approximately 1–2 mm in diameter are observed at the surface of the target.

Effect of Temperature on Emission from CaF_2 Films. The electron emission of a target with a CaF_2 film, which is produced when thetarget is bombarded by a beam of H_1^+ ions with energies from 10 to 40 kev and which continues after the bombardment, can be observed at temperatures ranging from −195 to + 80°C. The emission was not observed at temperatures above + 80°C. The emission from a target with a CaF_2 film 26–30 μ thick, produced by bombardment with a beam of H_1^+ ions with an energy of 10 kev at a temperature of −195°C, was observed continuously for 6 hours after thebombardment was terminated while the temperature of thetarget was gradually increased to +80°C. At + 80°C the emission current vanished sharply, but after target cooling to below + 80°C. and subsequent bombardment by the beam of H_1^+ ions, the emission was produced again with the same intensity and lifetime.

The results of a measurement of the cross-sectional resistance of a CaF_2 film 20–25 thick are shown in Table I.

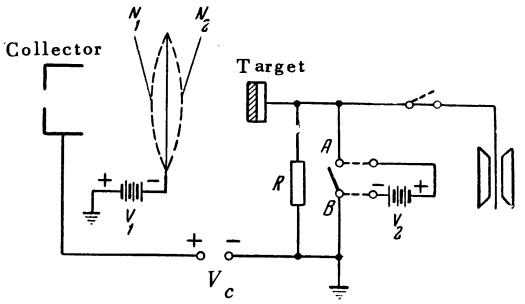

FIG. 6. Diagram of the arrangement used to measure thepotential of thetarget surface.

Observations with an Electron Projector. A film of CaF_2 was vacuum–evaporated on to a steel sphere 4 mm in diameter; the target was placed at the center of a spherical glass bulb, 100 mm in diameter (Fig. 5). The thickness of the CaF_2 film was 10–15 μ. A semi-transparent film of silver was deposited on the inner surface of the sphere; this served as a collector. The silver film was covered with a fine layer of ZnS. When the target of the electron projector was bombarded with a beam of H_1^+ ions with energy of 10 kev, electron emission was produced and continued after the bombardment was terminated. The electrons emitted at the target produced scintillations at the screen of theelectron projector. The luminescence pattern did not cover the entire screen but consisted of separate patches whose shapes kept changing.

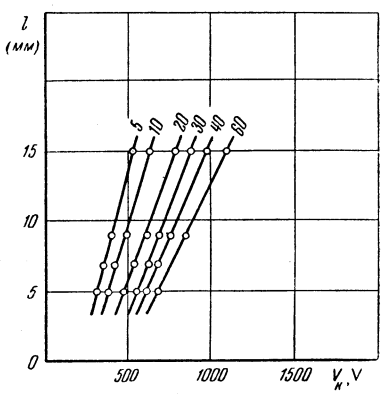

FIG. 7. The dependence of V_c on l for fixed values of I; the values shown on the curves are μ amps.

MEASUREMENT OF THE POTENTIAL AT THE SURFACE OF A TARGET WITH A CaF_2 FILM

A 3 μ Wollaston wire was placed on an insulator in the operating chamber (Fig. 6) between the collector and the target and an image of this wire was projected on the screen along with a scale. A fixed potential, V_1, was applied to the wire. A fixed potential difference, V_c, was set up between the collector and the target, causing the image of the wire on the screen to assume the position N_1. While the target was bombarded the image of the wire assumed the position N_2. After the bombardment of the target was terminated, the image of the wire was gradually restored to the position N_1. After several hours the image of the wire coincided with the original position N_1; then, without removing the potentials V_1 and V_c, the electrometer was disconnected and a potential difference V_2 was applied to the terminals A and B such that the image of the wire assumed the position N_2. The potential V_2 was taken to be the approximate value of the potential at the surface of the target. In various experiments, the potential V_2 varied from 180–220 volts for CaF_2 film thicknesses of 26–30 μ. Inasmuch as the electrons are emitted from a small portion of the target surface, it may be assumed that the potential of the emitting part of the target surface is greater than V_2.

TABLE II

Film thickness, μ	Electron emission current μ amp.	Target surface potential volts	Film thickness, μ	Electron emission current μ amp.	Target surface potential volts
45	5	380	43	25	690
45	20	330	43	18	520
45	25	630	43	20	520
45	30	555	43	20	570
45	22	346	85	2	760
45	51	450	85	2.5	590
45	51	520	85	3	555
45	42.5	450	85	5	830
45	81	520	75	14	330
50	0.7	470	75	19	340
50	0.4	380	75	32	450
			75	46	380

In measuring the potential at the surface of the target with CaF_2 films, use was also made of the method suggested by Dobischek, Jacobs and Treely.[4] It was shown that for a fixed value of the emission current, V_c changes linearly with the distance between the collector and the target l; the potential of the target surface was computed by extrapolating to $l = 0$. The dependence of V_c on l (Fig. 7) computed in the present work for fixed values of the current, using the voltage-current characteristics in Fig. 4, is also linear. In order to change the distance between the collector and the target smoothly, the target was fastened to the probe 10 of the micrometer screw 9 (Fig. 1). After the electron emission had been produced and the bombardment terminated, the disc-collector was positioned between the collector and the target. The diameter of the target was 20 mm and the diameter of the disc-collector was 45 mm. In changing the distance l, in order to maintain any desired fixed value of the electron emission current, it was necessary to vary V_c. Using the curves $V_c = f(l)$ for I= const, the potential at the target surface was calculated by extrapolating to $l = 0$. The surface potentials were measured in several targets and the results are shown in Table II.

I wish to express my sincere gratitude to Prof. K. D. Sinel'nikov for his valuable comments and continued interest.

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