Field-Dependent Secondary Emission

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Experiments have been conducted with magnesium oxide surfaces in which high dc fields were applied to the surface, while at the same time secondary emission measurements were being made. Very high secondary emission ratios were obtained reproducibly (100 to 1 and greater). Under static conditions it was found that the ratios would increase exponentially with increasing fields. In addition, for constant fields, the ratio of liberated electrons to bombarding electrons was constant, over a wide range of bombardment energy. Measurements were made of secondary emission with a square wave field applied to the surface and time lag effects were noted. Decay time in the order of 30 microseconds were measured. The rise time was found to be dependent upon field and bombarding currents. The mechanism of field dependent secondary emission was shown to be related to an avalanche effect, triggered by the bombarding electrons.

I. INTRODUCTION

THE concept of using an electric field to enhance secondary emission from composite surfaces has been of considerable interest in recent years.[1–4] Several experiments[5] dealing with field enhanced liberation of secondary electrons have revealed possibilities of obtaining ratios which are higher than ordinary secondary yields by a factor of 10 to 100.

Unfortunately, in most experiments of this type, the stability of the surfaces was poor, making accurate measurements difficult. In addition, pulse measurements were generally not made, nor were the potentials at the surfaces of the emitter measured, making quantitative analyses of the mechanism difficult.[6] As a result, there are several mechanisms suggested for field enhanced secondary emission, but little agreement exists amongst the various theories proposed.

In the following work to be described, a method was found whereby field enhanced secondary emission surfaces of MgO could be constructed reproducibly and which were stable over considerable periods of time. Currents as high as 10 milliampere/cm^2 could be drawn without immediate deterioration, and tests were extended over a period of weeks on the same samples. In addition, the potential at the surface of the sample could be estimated while, at the same time, the potentials of the base metal could be measured. Finally, measurements were made under pulse conditions and build up and decay times could be recorded and used for computations.

Before describing the experiments further, it might be best to first review the work of others in similar types of experiments. Malter[2] studied secondary emission surfaces prepared by electrolytically oxidizing aluminum and subsequently treating the surfaces with caesium and oxygen during the exhaust process. The maximum beam currents he used were 3 to 4 microamperes, under which conditions he sometimes observed a blue fluorescence of his target upon electron bombardment.

Malter found experimentally that the yield from his target increased as a power of his collector voltage:

$$I_c = B(V_c)^m, \tag{1}$$

where I_c = collected current, V_c = collector voltage, and B, m = constants.

His collector current was also found to rise as a power of the beam current. In addition he found that the surface exhibited long time lag characteristics. That is, after the primary beam was cut off, the secondary emission first decayed rapidly and then more slowly, persisting for many hours in some cases.

The theory that Malter and later Koller,[7] developed was that the high secondary emission ratios observed (i.e., 1000 to 1) were due to positive ions formed at the surface of the secondary emission material by electron bombardment. These positive charges were thought to reside on the surface for long lengths of time, due to the high resistivity of the film. During this surface ionization period, high fields could exist in the material and electrons could be liberated in greater quantities due to the field.

Pensak[5] did some work too, which may be pertinent, although he studied conductivity rather than secondary emission. In his experiments, steady bombarding currents, penetrating a thickness of amorphous silica film, induced a conductivity producing a current of one hundred times the bombarding beam. He used a double-beam technique, to measure the potential at the surface.

The beam used for inducing conductivity was kept at about 10,000 volts and 0.02 μa. He concluded that the induced currents were proportional to the energy absorbed by the beam, and that the beam in question must have sufficient energy to penetrate the film for induced conductivity. It was found too, that an increase in induced currents could be obtained with an increase in field across the insulator. No time lag measurements were specifically referred to in this article.

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[2] L. Malter, Phys. Rev. **50**, 48–58 (1936).
[3] E. R. Piore, Phys. Rev. **51**, 1111 (1937).
[4] H. Nelson, Phys. Rev. **57**, 560 (1940).
[5] L. Pensak, Phys. Rev. **75**, 472–478 (1949).
[6] K. G. McKay, *Advances in Electronics* (Academic Press Inc., New York, 1948), Vol. I., p. 108.
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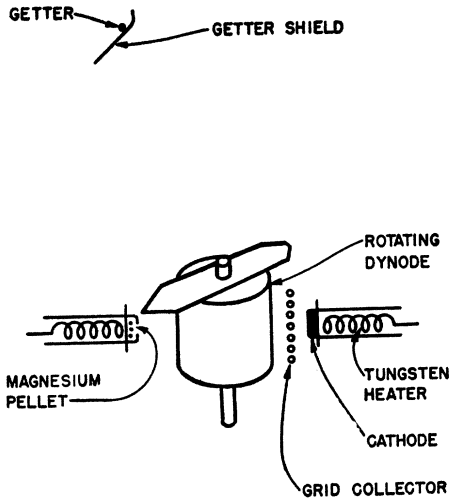

FIG. 1. Arrangement of parts in experimental tube.

The work described in the magnesium oxide experiments reported in this paper differs from that of Malter and Pensak in the following respects.

The chemistry and preparations of the surfaces are not similar.

In the work of Malter, collector current varied as a power of bombarding current and collector voltage. In the experiments to be described, collector current varied linearly with bombarding current and increased exponentially with field.

In Pensak's experiments high energy electrons were used (10,000 volts) such that the beam could penetrate through the material. In addition he measured conduction current rather than secondary current. In the work to be described with magnesium oxide, the bombarding electrons were low in energy (100–300 volts). This indicated that electron penetration of the surface was not required. In addition relatively high current densities could be used. As will be shown, high currents make possible the use of shorter time lag effects.

Finally, by means of these experiments, a piece of evidence was obtained concerning the mechanism of these field enhanced secondary emission effects. An avalanche-type theory is proposed whereby electrons, being accelerated by high fields, produce additional electrons within the volume of the material, which in turn leads to an avalanche similar to the gas discharge type of build up of presparking current.

II. EXPERIMENTAL PROCEDURES

The arrangement of parts used in experimental tubes for the study of field dependent secondary emission, is shown in Fig. 1.

The tube consisted of a cylindrical cathode coated on one end; a grid, to be used as accelerator and collector, and a dynode which could be rotated by a magnet external to the tube. On the side of the dynode, opposite the cathode, was another cylinder containing a magnesium pellet which could be evaporated upon heating by applying current to a filament contained by the cylindrical sleeve.

The purpose of this arrangement was as follows. At exhaust, the cathode (BaO–SrO) could be activated, the grid bombarded and parts heated by an induction furnace without contaminating the opposite side of the dynode, which was kept facing the magnesium pellet. After this initial tube processing and activation of the cathode, oxygen was admitted to the system (about 80 microns) and the magnesium was slowly evaporated to the dynode to a thickness of 10^{-5} to 10^{-4} cm. The oxygen was then pumped out of the vacuum system and the cathode reactivated. The cathode temperature was lowered to about 300°C to 400°C, and the MgO deposited on the anode, was then rotated in front of the cathode for test. (The oxidation process sometimes involved induction heating of the evaporated Mg on the dynode in the presence of oxygen. This technique worked equally as well.)

The use of the rotating dynode greatly reduced the possibility of contaminating the secondary emission surface, since during cathode activation the surface was shielded. When the surface was rotated back in front of the cathode for test, the cathode temperature was reduced to where only 1 to 10 μa could be drawn as temperature limited emission. Under these conditions the barium evaporation was negligible and previous experiments indicate that the barium evaporation would not interfere with results.[8,9]

At static test, the circuit used was as indicated in Fig. 2 and is somewhat standard set up for measuring dc secondary emission yields.

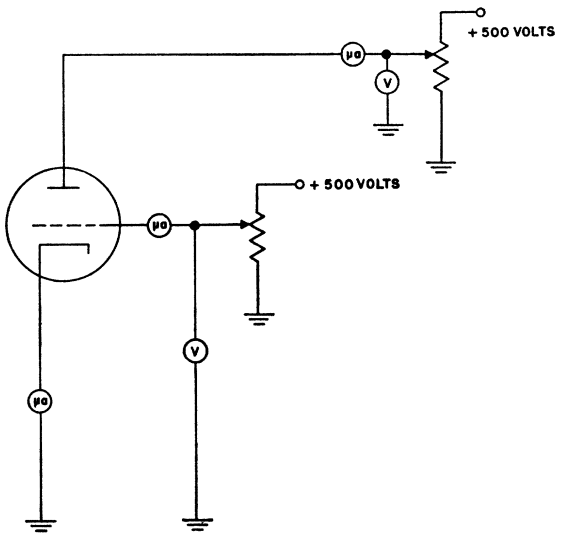

FIG. 2. Static test circuit.

[8] H. Jacobs, J. Appl. Phys. **17**, 596 (1946).
[9] J. B. Johnson, Phys. Rev. **73** 1058–1073 (1948).

III. STATIC TEST DATA AND INTERPRETATION

In testing the tube under dc conditions, the dynode was set at about 100 volts, the grid was then raised to about 225 volts, and the cathode was near ground potential (see Fig. 2). Secondary emission ratios of 100 to 1 were readily attained (Fig. 3, tube No. 2). In addition, it was found that the secondary emission ratio changed roughly exponentially with the change of the difference of potential between the collector grid and the dynode plate (Fig. 4, tube No. 3 and Fig. 5, tube No. 4). Thus, if one would use an equation the following relation would hold over a limited region.

$$\sigma = A\epsilon^{+\alpha(E_g - E_p)}, \qquad (2)$$

where σ=secondary emission ratio, A, α=constants over a limited region, E_g=grid potential (collector), and E_p=plate potential (dynode).

In all, seven tubes were constructed with MgO on the dynode and all showed similar behavior. The collector voltage increment would appear to bring about an exponential increase in collector current for a given bombarding current, with a slight bending of the curve downward as the higher ratios are approached. This differs from Malter's work in which he found that for constant bombarding current, the yield varied as a power of the collector potential.

In Fig. 4, we see the results of bombarding the surface under different bombarding energies. The data indicates

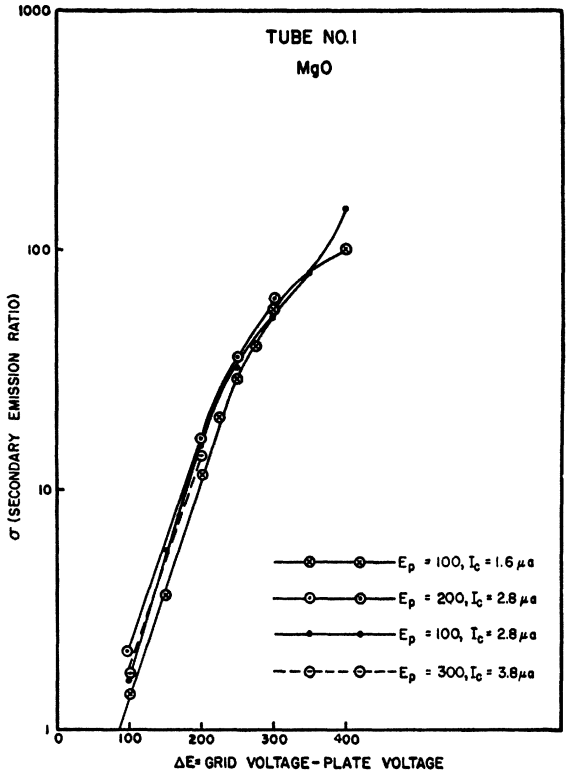

FIG. 4. Secondary emission ratios as a function of field, with various bombarding energies.

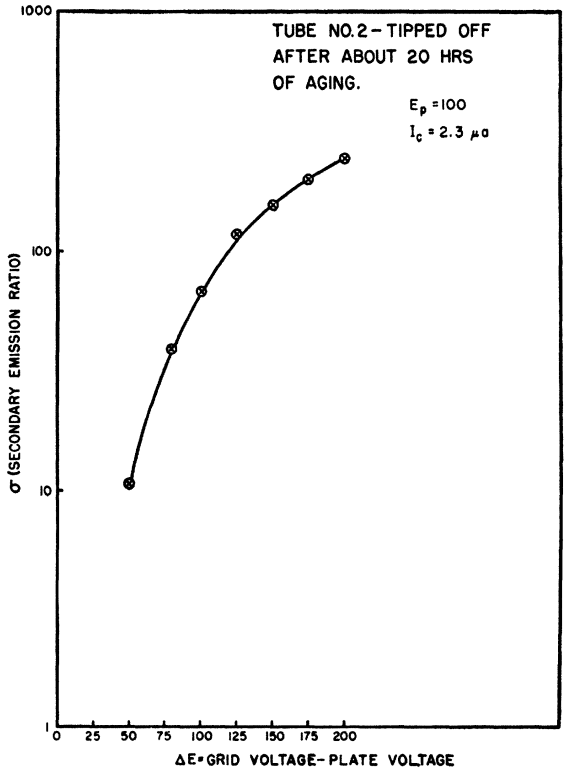

FIG. 3. Secondary emission ratio as a function of field.

that for a given field (collector voltage minus the dynode voltage), the secondary emission yield is independent of the potentials on the collector and dynode. In the first run, indicated by points marked ⊗, the dynode set at 100 volts yielded a ratio of about 60 to 1 with 400 volts on the collector. In the second run, indicated by ⊙, the dynode was set at 200 volts and collector at 500 volts. The secondary ratio was still near 60 to 1. The results indicate that the electric field effects the secondary emission ratio in such a way, that the yield is independent of bombarding energies, in the region studied. The bombarding currents in these tests, were kept in the same order of magnitude.

In Fig. 5, there is further evidence that the ratio of collected current to bombarding current is a function of field (the difference of potential between the collector grid and the dynode plate).

In some cases at high bombarding currents (100 μa or greater) a blue fluorescence appeared on the surface bombarded. This afforded a fair approximation of the area being bombarded. The area changed very little with dynode plate voltage. Several tubes were constructed too, with "willemite" phosphor coated over the dynode. These tests confirmed the conclusion that bombarded spot size did not change appreciably in the voltage ranges studied.

In previous, unpublished experiments it had been found that MgO surfaces, prepared similarly, except

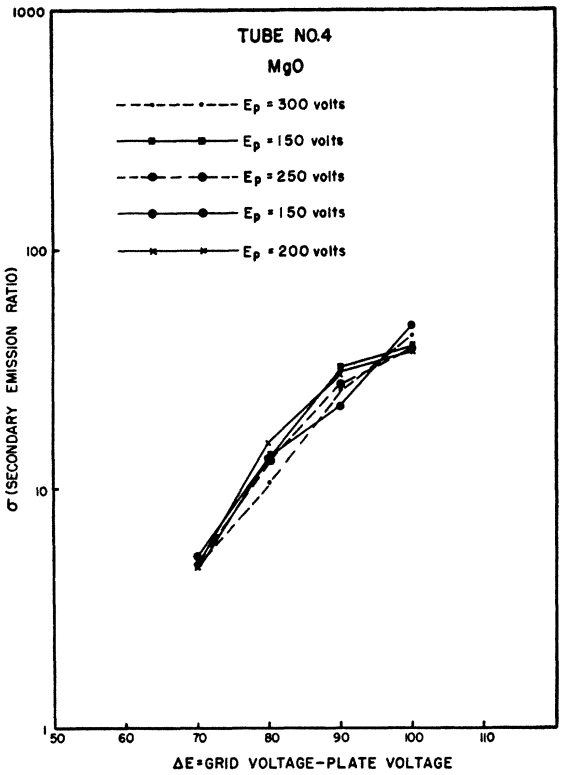

FIG. 5. Secondary emission ratios as a function of field, with various bombarding energies. Conclusion: σ is dependent only upon field and not upon bombarding voltage.

made more conductive, and not showing field dependence, yielded ratios in the order of 4 to 1 or 5 to 1. This can be interpreted as the true secondary emission yield of the surface, especially inasmuch as the accelerating fields have practically no effects on the ratios.

The large secondary emission yields would have to be due to a high accelerating electric field, active on the surface simultaneously with the bombardment. This high field would be due to positive charges built up on the outer surface of the MgO. If charges did not exist, the field would be the difference in potential between the grid and plate divided by the distance, or a ratio of roughly 100 volts/0.2 cm, giving a field of 500 volts/cm. Such a low field could hardly provide the acceleration for such high electron ratios. Suppose however the MgO surface charged due to the liberation of secondary electrons and the high resistance of the material preventing a rapid decay of charging. In this case it would be possible for the surface to charge to the same potential as the collector and if the thickness were 10^{-4} cm, the field would be 100 volts/10^{-4} cm $= 10^6$ volts/cm. At 10^6 volts/cm one could expect field enhanced secondary emission. Another piece of evidence supporting the premise that about 10^6 volts/cm is really across the surface material is the fact that under the test conditions the material is very close to arcing. When the high ratios are attained a tendency for arcing increases. The data represented in Figs. 3–5 was taken in the region just prior to arcing.

TABLE I. Secondary emission ratio (σ) as a function of difference in potential (ΔE) across the dielectric at different bombarding energies.

E grid	E plate	ΔE	σ	Filament potential 2.3 volts
450	350	100	10.5	
400	300	100	12.0	
350	250	100	11.6	
300	200	100	11.0	Bombarding current
250	150	100	11.1	1.5 μa
200	100	100	5.7	
150	50	100	3.15	
125	25	100	1.9	

The surface charging theory makes more intelligible the uniformity of the effects of field on secondary ratios. For a given tube, such as No. 4 (Fig. 5), the thickness of the film would be relatively constant. If we assume that the dynode surface charges to the potential of the grid collector, then the difference in potential from grid to plate would be the difference in potential across the surface film. This difference in potential would then be a measure of the field across the dielectric. By measuring the difference in potential from grid to plate we would then be measuring effectively the field accelerating secondary electrons generated in the volume of the material. The pulse measurements made in the latter part of this report confirmed this statement. To summarize the first part of this interpretation, the secondary electron ratio was found to be exponentially dependent upon the field across the dielectric during bombardment. In the region mentioned, the energy of the bombarding electrons do not effect the yield ratio.

Another experiment was tried with tube No. 7 to determine where the bombarding energy effects are important. In this test the bombarding current was constant, the plate and grid voltages were varied, but in such a manner that the accelerating field was kept constant. The ratio was found to be constant down to a plate voltage of 150 volts and a grid voltage of 250 volts (see Table I).

This would indicate that at the higher energies, the yield was such that for 1.5 μa bombarding current, the surface charged to the potential of the grid and in this region the yield is independent of primary beam energy and only dependent upon field. When the dynode was 100 volts and lower however, the yield and currents were such that the surface could not charge up completely and the equilibrium ratios were considerably lower.

Another experimental point of interest was the effects of bombarding currents upon the secondary yield. In the work of Malter the collector current was found to vary as a power of the primary current. In our experiment however, the collector current varied linearly with bombarding current. This provided a ratio that was constant as the primary current varied.

In Fig. 6 tube No. 7, we see the results of an experiment in which the field across the dielectric (E grid-E plate) was kept constant for two different settings. In each run the only factor varied was the primary beam current density. In both cases the plate was set at 150 volts. In the first case the grid was kept constant at 260 volts, and in the second case the grid was kept constant at 270 volts. The results show that the bombarding current densities do not cause a change in the secondary emission ratios. In another tube (No. 5) the primary beam was varied by a factor of 70 without appreciable change in the ratio.

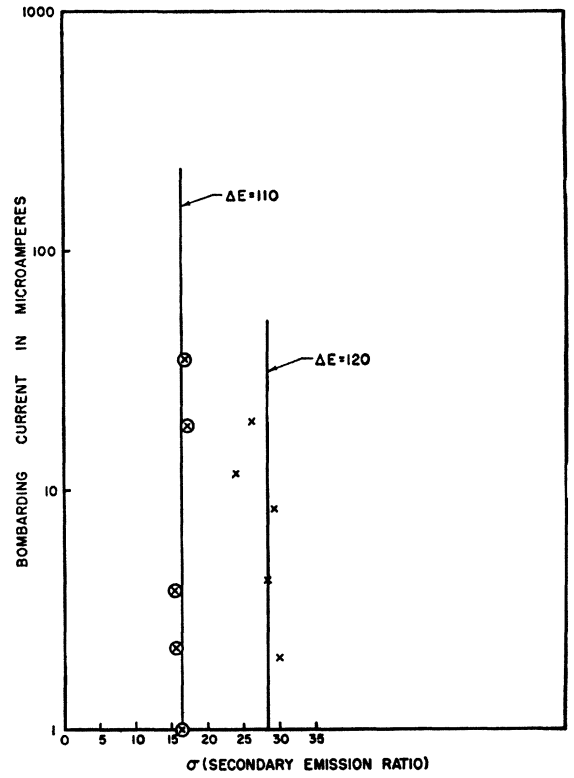

FIG. 6. Secondary emission ratios with constant fields and varying bombarding current densities.

IV. DYNAMIC TEST DATA

In Fig. 7 we see the circuit used to apply a square wave field on the surface. The cathode was temperature limited such that variations in grid potential caused little or no variation in bombarding current. A small resistor of 6000Ω was used as an indicator of the current in the dynode circuit, and the grid and dynode were set at 275 volts and in the order of 190 volts respectively. a square wave of ±20 volts was placed on the grid, such that the grid rose to 295 and dropped to 255 volts at various frequencies.

The purpose of these experiments was to determine the rise and decay times for the field dependent secondary emission and to isolate the factors most concerned, such as bombarding currents and fields.

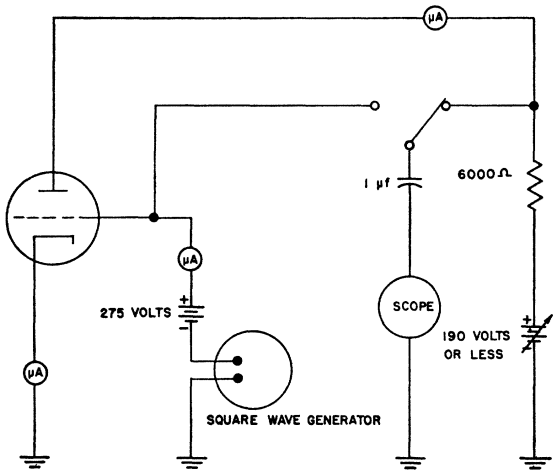

FIG. 7. Dynamic square wave test circuit.

First, the effects of field on rise time was analyzed. The cathode current (bombardment current) was kept constant and the dc voltage on the grid was set at 275 volts. The square wave was applied at a frequency of 200 cycles per second. The plate was set at about 190 volts, and then lowered to increase the field across the dielectric and at the same time, to increase the secondary emission yield. In Fig. 8 we see the results of the increasing field upon the time necessary for saturation. At the low level of fields, saturation was not found to be completed in the time allowed. However, as the field was increased the shape of the curve changed and saturation started to become apparent. Saturation would indicate a completion of positive charging of the

200 CYCLES/SECOND SQUARE WAVE ON GRID
BOMBARDING CURRENT = 10.5 μa AND KEPT CONSTANT

OSCILLOSCOPE CHARACTERISTIC ACROSS DYNODE RESISTOR	MAXIMUM GRID POTENTIAL MINUS PLATE POTENTIAL	MINIMUM GRID POTENTIAL MINUS PLATE POTENTIAL	CHANGE IN SECONDARY EMISSION RATIO
	105 VOLTS	65 VOLTS	3
	115	75	6
AMPLITUDE ↑	125	85	10.3
	135	95	15
NOT COMPLETE SATURATION	145	105	24.3
1/200 SEC.	155	115	48

FIG. 8. The change in rise time with increasing difference in grid potential and plate potential.

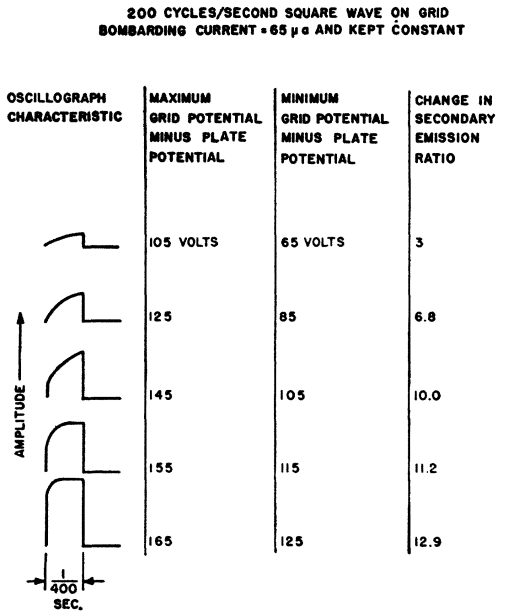

FIG. 9. The change in rise time with increasing difference in grid potential and plate potential.

surface in order for the surface to attain the potential of the grid. We might conclude from Fig. 8 that a higher dc field causes a higher rate of surface ionization and hence a shorter rise time for the secondary electron yield. In Fig. 9 we see a similar run for a higher bombarding current. Again we see that the increased field decreases the rise time. In addition, it was found that higher bombarding currents decreased the rise time. This is consistent with the concept of surface charging, since the greater number of electrons striking the surface, the greater the surface ionization and hence the shorter the rise time. Similarly, the field should increase the rise time because, as the field is higher, the number of secondaries produced and thus the number of positive ions near the surface increases. As a qualitative estimate it would seem that the rate of rise of secondary emission was more sensitive to increasing bombarding currents than increased field.

In the next tests, care was taken to maintain the fields constant, and thus the secondary emission constant while varying only the bombardment current. In Fig. 10 we see that the increase in bombarding current decreases the rise time, under the action of a square wave (100~/second) field applied to the grid.

As another means of illustrating the effects of bombardment current upon the rise time another experiment was tried in which the fields during the testing were kept the same, and the bombardment current was varied. At low frequencies, i.e., 20 cycles per second, saturation was easily attained. However, as the frequency was raised, at constant amplitude, the "saw tooth-like" appearance of dynode current started to appear. On further increasing the frequency, the dynode current no longer reached the saturation values and the amplitude of the top of the "saw tooth" started to decrease. Measurements were made of the frequency of the square wave required to decrease the maximum response to one half its saturation value. In Fig. 11, we see that as the bombardment current increases the rate of rising increases, in that higher square wave frequencies are required to halve the output.

Measurements were also made on decay times and these were found to be in the region of 15 to 40 microseconds. The decay time may be related to bombardment current, as this could discharge the surface more rapidly than the resistance of the material.

V. INTERPRETATION

The pulse data supplied additional evidence that the high yields are associated with charging of the surface. If we assume that the surface film resistivity is high then the following relation exists.[10]

$$E=(\sigma-1)j_p t\times 1.13\cdot 10^{11}/K \text{ volts/cm}, \qquad (3)$$

where E=field developed across dielectric, σ=secondary ratio, j_p=bombardment current, and t=time. In an actual case, for saturation to be reached, $t=(1/800)$ sec, and $j_p=65\times 10^{-6}$ amp. Assume $K=3.5$, and $E=10^6$ volts/cm. Then $\sigma=5.6$. In the actual case σ rose from 10 to 15, thus placing the calculated σ near the correct order of magnitude. This calculation is another piece of evidence that the high field developed, is across the dielectric and not from grid to dynode.

Something might be inferred here concerning the mechanism of the discharge. As was mentioned, the

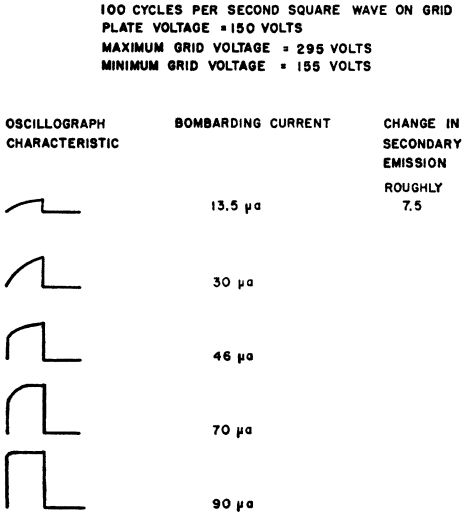

FIG. 10. Change in rise time with increasing bombarding current.

[10] See reference 6, p. 109.

films were operated in the region just prior to arcing. There have been two major schools of thought concerning this pre-arcing region. One group believes that pre-arcing currents are due to tunnel penetration of electron from the cathode into the material. Using the Fowler-Nordheim equation, the currents over a small change in field should be an exponential function of field. The alternative theory, which also yields an exponential form, is that a free electron, accelerated by a high field, will free other electrons with an avalanche resulting.

The Fowler-Nordheim relation is given in Eq. (4) and the avalanche expression in Eq. (5).

$$J = CF^2\epsilon^{-D/F}, \tag{4}$$

where J = current density, F = field,[11] and C, D = constants.

$$N = N_0\epsilon^{\alpha X}, \tag{5}$$

where N = Number of electrons released, N_0 = initial number of electrons, X = distance, and α = Number of electron formed/cm of path/incident electron (varies with field, F).[12]

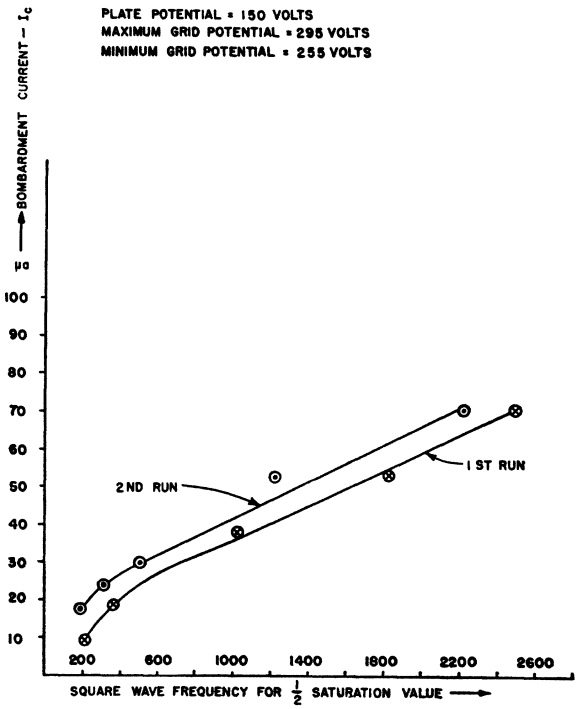

FIG. 11. Bombardment current *versus* frequency required for one-half saturation value of secondary emission.

The experiments tell us that essentially Eq. (5) is the correct expression and that the avalanche theory is more plausible. If field emission were correct, the collector current would have been independent of bombardment current, provided enough current were present to establish a high field across the dielectric. In practice, it was found that for a given field, the ratio of secondaries to primaries was constant. Referring to Eq. (5), N/N_0 = a constant, independent of the size of N_0, providing the field (F) and distance (X) are constants. If we assume that an electron penetrates a distance X, which does not change much for the case of a 150-volt electron to a 250-volt electron, the experiments verify Eq. (5). The ratio was found to be constant for a constant field (see Figs. 3–6).

VI. CONCLUSIONS

Under conditions of intense electric fields, specially prepared magnesium oxide films show high secondary emission ratios. Under static condition, the secondary emission ratios have been found to be an exponential function of the field. Ratios of 100 to 1, with 100μ a/cm^2 of bombarding current and 10 ma/cm^2 collecting current was readily attained.

Under pulse conditions decay times in the order of 30 microseconds were found. The rise time was found to change depending upon bombarding currents and fields, shorter rise times being noticed with higher fields or higher bombarding currents.

[11] The field could vary if the resistance should change under bombardment. However, in the work of Pensak and others, the resistance is constant until the primary beam actually penetrates the thickness of the dielectric. This would require far greater than 10,000 volts. It can therefore be assumed that the film resistance does not change markedly and that F is constant under equilibrium conditions.

[12] In using Eq. (5), it might be well to discuss the meaning of the symbols and derivation of the equation. In the early days of gas discharge studies, J. S. Townsend used the equation in the following manner. He regarded n as the initial number of electrons (or negative particles) per second crossing one square centimeter of surface. A number of new ions dn, proportional to n and to length dx, would be produced by electron collisions. The rate of increase, or the proportionality constant, was called α. If diffusion and recombination could be neglected, $dn = \alpha n dx$, and $N = N_0\epsilon^{\alpha X}$. N_0 represents the initial number of electrons per second crossing the unit area, and N represents the total number of electrons obtained.

Towsend did some further work on the nature of α, the probable number of ionizing collisions, per centimeter of path, per electron. He attempted to interpret in terms of field, mean free path of the electron, and ionization potential. However, the theoretical aspects of this interpretation have not proved to be correct in later years. Today, it is admitted that an empirical relationship does exist for α in terms of field, pressure and ionization potential, but the exact theory is by no means clear. It has been found experimentally, for low regions of field/pressure, that α/p varies nearly linearly with F/p, where p = pressure, over small ranges of field.

In the experiments described above, the magnesium oxide film was regarded as a high pressure gas, with the bombarding electron releasing additional electrons within the material. The released electrons, accelerated towards the surface, could then release additional electrons in a manner similar to the "Townsend Avalanche". The resulting electrons could then be accelerated into the vacuum by the positive charges on the surface of the magnesium oxide. Since α/p was found to be a linear function of F/p in gas ionization, at low F/p values, we might expect α to vary linearly with F in a solid, where p could be considered constant. Thus, over a limited range one might find N to vary as an exponential function of field, F.

For further details of the gas discharge concepts the reader can find a summary in J. D. Cobine, *Gaseous Conductors* (McGraw-Hill Book Company, Inc., New York, 1941), 147–154.

Both static and dynamic tests indicated that the field was being applied directly across the dielectric due to a positive charging of the secondary emission surface caused by the emission of secondary electrons and the high resistivity of the film.

The mechanism of the high yields has been suggested as an avalanche type of discharge due to liberation of electrons by high velocity electrons in the volume of the material near the surface.

Acknowledgment is made to Mr. Jack Martin, Mr. G. Hooker, and Mrs. Margaret I. Holmes for their help in the testing and construction of experimental tubes; and to Dr. J. E. Gorham and Dr. L. Pensak for their advice during the course of this work.

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The $Al^{27}(d,p)Al^{28}$ and $Al^{27}(d,d')Al^{27}$ Reactions*

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A large heavy-particle magnetic spectrometer was used to study the proton and deuteron groups from the deuteron bombardment of a thin aluminum foil. Charged particles emitted at 90 degrees with respect to the the incident deuteron beam were analyzed by momentum in an annular-shaped magnetic field. Groups of protons and deuterons correspond to excited states in Al^{28} and Al^{27}, respectively. Fifteen groups of protons from the reaction $Al^{27}(d,p)Al^{28}$ were observed. Their Q values were 5.53, 4.49, 3.95, 3.36, 3.01, 2.06, 1.55, 0.70, 0.37, −0.27, −0.60, −0.84, −1.37, −1.86, and −2.98 Mev. The elastically scattered deuterons and five groups of inelastically scattered deuterons were also observed. Their Q values were 0, −0.97, −2.39, −3.17, −4.74, and −5.76 Mev.

I. INTRODUCTION

McMILLAN and Lawrence[1] first discovered that the protons from the deuteron bombardment of aluminum consisted of several groups. Since then this reaction has been studied by several observers[2–4] In this experiment 10-Mev deuterons bombarded an aluminum target in a magnetic spectrometer capable of focusing 15-Mev protons on a nuclear research emulsion, which was used as a particle detector. A search was made for proton groups corresponding to excited states in Al^{28} up to 9 Mev above the ground state.

The inelastic scattering of deuterons was first reported by Greenless, Kempton, and Rhoderick[5] in 1949. They observed two groups of deuterons inelastically scattered by aluminum. Holt and Young[6] subsequently observed these two deuteron groups and gave Q values (Q values and energy levels have the same magnitude for inelastic scattering but opposite signs) of -0.99 ± 0.05 and -2.17 ± 0.05 Mev. In the present experiment, the scattered deuterons were recorded simultaneously with the protons in the nuclear emulsions.

II. APPARATUS

A large charged-particle spectrometer, having 180° magnetic focusing, was made, using an annular magnet similar to one described by Cockroft.[7] The mean radius of the annulus is 42 cm, the width of the annulus is 8 cm, and the width of the gap between the pole faces is 0.658 cm. A collimated beam of deuterons from the Washington University cyclotron passes through a small hole in the magnet pole face and strikes a 0.2-mil aluminum target in the gap between the pole faces. The particles from a nuclear reaction which leave the target at 90° with respect to the incident beam travel in the evacuated gap between the pole faces of the annular magnet. The magnetic field in the gap can be adjusted from nearly zero to about 16,000 gauss. With a given magnetic field, all of the particles in a certain momentum interval will stay in the annulus through 180° and strike a nuclear photographic plate inclined in the magnet gap. The angle of inclination of the nuclear plate is 12° with respect to the pole faces. The plate is attached to a holder equipped with a long rod which is used to insert the plate between the pole faces of the magnet. This rod enables the plate holder to be placed in an air lock, which is then evacuated. The valve to the main vacuum system is opened and the plate is pushed into position between the pole faces.

The magnetic field of the annular magnet is produced by a current of up to two amperes in a water-cooled coil situated between the magnet core and the pole faces. The constant magnet current is supplied by a grid-controlled thyratron rectifier.

The magnetic field was measured with a Leeds and Northrup ballistic galvanometer in series with a flip coil which is located in the half of the annulus through

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