Energy Distributions of Field Dependent Secondary Electrons

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Retarding-potential experiments were conducted to determine the energy spectrum of electrons emitted from thin films of magnesium oxide under conditions of field-dependent secondary emission.

The present method is correlated to the techniques utilized for probe studies in a gas plasma, and a means of determining the apparent surface potentials on the magnesium oxide films is indicated. Determinations of electron temperatures and velocities as a function of the applied field are made, based upon this correlation.

The spectrum, having a spread from zero up to ninety electron volts, is shown to be Maxwellian with average energies ranging between ten and twenty electron volts, depending on the applied field.

I. INTRODUCTION

RECENTLY we reported the results of a study on field dependent secondary emission from thin, porous films of magnesium oxide.[1] At that time, a mechanism, based on the principles of the gas discharge laws, was proposed to describe the effects noted when thin films of magnesium oxide were bombarded with electrons. It was found that an equation of the form

$$i=i_0e^{\alpha x}, \tag{1}$$

where i is the secondary current, i_0 is the primary or bombarding current, α is the number of new electrons formed per centimeter per electron, and x is the depth within the film at which an ionizing event occurs, would accurately describe the experimental results.

Briefly, the theory may be stated as follows: primary electrons bombard the magnesium oxide film creating a positive surface charge due to ordinary secondary emission in combination with the relatively high resistivity of the semiconducting layer. Previous measurement had shown the film thickness to be 10^{-4} cm.[1] Thus a high field is formed across the film as a result of the surface charge. Subsequent bombarding electrons penetrate into the porous film and create secondaries. Then, under the influence of the high field, the liberated secondary electrons can gain sufficient energy to cause further ionization. The process continues until an equilibrium avalanche is established.

In an attempt to gain further information regarding the fundamental processes involved, a study was made of the energy distribution of the emitted electrons.

II. EXPERIMENTAL PROCEDURES

A. Tube Design

The fact that the gas discharge theory and equations could be used to explain the previous experimental results suggested the possibility that a method for analyzing the energy spectrum might be found in that field. Accordingly, a technique utilizing retarding potentials and based on the theory of probes in a gas plasma,[2] was found to provide a simple, direct and reasonably accurate means of measuring the electron energy distributions.

The tube employed in these experiments is illustrated in Fig. 1, and the test circuit is shown in Fig. 2. Essentially, the tube structure consists of a magnesium evaporator (not shown in either sketch) for depositing the magnesium through low pressures of oxygen onto a cylindrical anode. After evaporation, the dynode

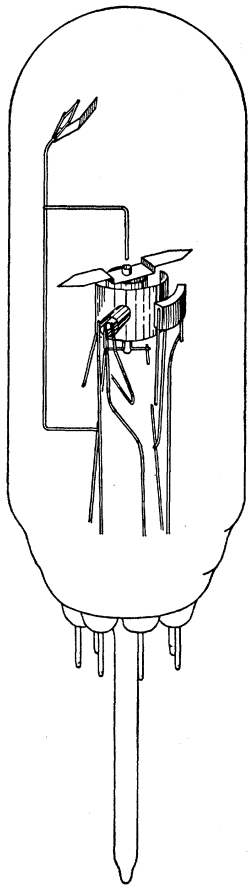

FIG. 1. Structure of vacuum tube utilized in determining electron energies and surface potentials.

[1] Jacobs, Freely, and Brand, Phys. Rev. 88, 492–499 (1952).

[2] See, for example, L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), pp. 232–257; J. D. Cobine, *Gaseous Conductors* (McGraw-Hill Book Company, Inc., New York, 1941), pp. 134–142.

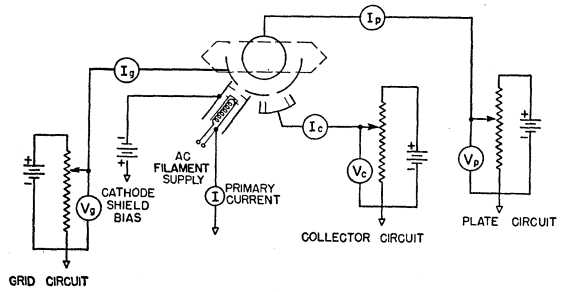

FIG. 2. Test circuit.

could be rotated, by means of a magnet external to the tube envelope, to place the newly formed magnesium oxide film in front of the grid structure. The grid, consisting of a solid, semicylindrical sheet, has two small holes to allow the passage of electron beams. One aperture, directly facing the cathode gun, allowed the primary beam to enter and bombard the film. The other hole, just opposite the collector electrode, permitted a portion of the emitted secondaries to pass through the grid and be recorded at the collector. The collector electrode, fabricated in the form of a box, had its inner surface coated with carbon black in order to reduce the possibility of reflected electrons.

Tube processing, exhaust, and magnesium oxide deposition were carried out in accordance with procedures previously reported.[3]

In previous experiments it was noted that the MgO surfaces exhibited a faint blue fluorescence while emitting electrons. The present tube design was based upon the assumption that the area of fluorescence was very nearly the same as the area of emission. If this were the case, it would be a simple matter to place a relatively large portion of the emitting area directly in front of the collector hole and still have part of it in line with the primary beam. If, on the other hand, the area were small it would not be possible to orient the emitting area so that both grid aperatures faced the active area at the same time.

In order to justify the assumption that the area of emission coincides with the area of fluorescence, parts of a tube were dusted with willemite prior to processing. The completed tube was then operated under standard conditions (see following section), while observations were made on the degree of fluorescence as various circuit parameters were changed.

It was observed that the inner surface of the grid exhibited a typical willemite fluorescence over an area almost exactly corresponding to the area of MgO fluorescence. In addition, the location and intensity of both grid and MgO fluorescence were not affected by potentials applied to the collector.[4]

[3] H. Jacobs, Phys. Rev. 84, 877 (1951).

[4] Experiments similar to the foregoing were carried out by L. R. Koller and R. P. Johnson in relation to the Malter effect [Phys. Rev. 52, 519–523 (1937)].

These results verified the original assumption and indicated the general feasibility of the present approach.

In operation then, a large fraction of the emitting area is placed before the collector aperture and one may assume that the electrons leave the MgO normal to the surface.

B. Testing Procedures

After exhaust and processing, the circuit of Fig. 2 was used to make direct measurements of the energy spectra and surface potentials in the following way: a small negative (with respect to ground) voltage was applied to the cathode shield in order to achieve a close definition of the primary beam. Positive potentials of approximately 100 and 200 volts were applied to the dynode and grid respectively. Under these conditions, the surface of the magnesium oxide film acquired a positive charge, and a controlled equilibrium avalanche current was established. Positive potentials were then applied to the collector in small steps and the collector current was measured while holding all other parameters constant. Similar sets of data were taken for various values of the electric field in the magnesium oxide film. The field was varied by changing either the grid or dynode potentials.

It should be noted that until the collector reaches the same voltage as that of the magnesium oxide surface, its potential is negative or retarding with respect to that of the surface. Hence, any electrons which reach the collector under these conditions must do so by virtue of their initial velocities.

III. EVALUATION AND INTERPRETATION OF EXPERIMENTAL DATA

According to the theory of probes,[5] a semilog plot of probe current as a function of probe potential will provide direct information regarding the plasma potential and electron energy distribution. Figure 3 shows a series of curves representative of data obtained in the present experiment. Figure 4 illustrates similar data but with retarding potential as the abscissa.

The curve of Fig. 4 may be readily interpreted in terms of electron energies. At point A, only electrons possessing very high initial velocities are recorded. At point B, electrons of medium as well as high energies are measured, and finally at C, electrons of all energies, including zero, are noted. At C then, the collector potential must equal the surface potential if zero energy electrons are being recorded. Hence, the knee of the

[5] Actually, one does not have to follow the probe analogy for the present case. We can simply imagine the tube to be a diode, with the collector as the anode and the magnesium oxide film as the cathode. The grid then is necessary only to maintain the discharge and need not receive direct consideration. The general development employed here, however, would still be applicable since electrons emitted from a thermionic cathode also follow a maxwellian energy distribution.

curve provides a measure of the surface voltage,[6] just as an analogous interpretation is made in the measurement of plasma potentials. Beyond C, the collector current exhibits a saturation tendency which is to be expected if the tube is free of any electron space charge. A second method of determining surface potentials has been developed and the results were found to check very well.[7] Surface voltages determined by both methods were observed to be from 20 to 30 volts lower than the grid potential, which would make the voltage across the MgO film about 80 volts, depending on electric field and current.

Following the gas discharge analogy further, one determines from the linear logarithmic variation of current with voltage (see Figs. 3 and 4), the energy distribution of emitted electrons to be Maxwellian. If this is the case, it is possible to calculate certain physical quantities which are of interest, such as the average electron energy and electron temperature.[8]

For a Maxwellian distribution, the average electron energy ($\bar{E}$) is determined by

$$\bar{E}=\tfrac{3}{2}(0.434)/m, \tag{2}$$

where m is the slope of region A-C in Fig. 4, and (0.434) is the ratio of common to natural logarithms. The electron temperature (T_e) is given by

$$T_e=0.434(1/m)(e/k), \tag{3}$$

where e is the electronic charge and k is Boltzmann's constant.

Now, from the electron temperature, we may

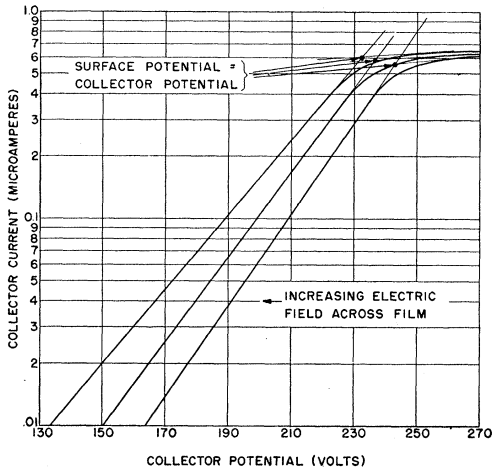

FIG. 3. Collector current as a function of collector potential. The variation of electron energies and surface potentials as a function of the electric field are also illustrated.

[6] A similar approach was utilized by Nelson in measuring the potentials of luminescent screens [J. Appl. Phys. **9**, 592–599 (1938)].

[7] Dobischek, Jacobs, and Freely, Phys. Rev. **91**, 804–812 (1953).

[8] J. Millman and S. Seely, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1951), pp. 286–289. See also reference 3.

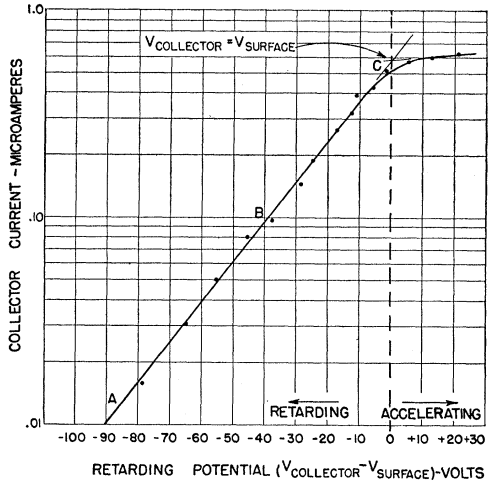

FIG. 4. Collector current as a function of retarding potential (dynode potential 100 volts and surface potential 226 volts), assuming the knee of the curve to represent zero surface potential.

calculate the average velocity ($\bar{v}$) of the emitted electrons according to the following expression:

$$\bar{v}=1.128[(2/m)kT_e]^{\frac{1}{2}}, \tag{4}$$

where m is the electron mass. This equation provides a means of experimentally determining the average velocity based on the slope of the curves in Figs. 3 and 4.

It has previously been pointed out that the knee of these curves is a direct measure of the surface potential, and since the film thickness is known to be approximately 10^{-4} cm, the electric field developed across the dielectric is also experimentally determined. Figure 3 illustrates the manner in which the surface potentials and average velocities change with increasing electric field.

We now seek an expression relating the average velocity to the field in the film. The gas discharge equations again provide a suitable answer in the following expression:[9]

$$\bar{v}=(2^{1/4}/\pi^{1/8})[(e/m)EL_e]^{1/2}, \tag{5}$$

where E is the electric field in the magnesium oxide and L_e is the mean free path of electrons in the film. The assumption is made here that all collisions are inelastic. Based on previous considerations,[10] L_e is estimated to have a value of 10^{-5} cm. From Eq. (5) a linear curve may be plotted for the average velocity as a function of the square root of the field. Equation (4), together with the experimentally determined values for electron temperatures and electric fields, may be used to obtain a similar, but purely experimental, plot. Figure 5 is a comparison of these two plots, in which the lower curve is based on Eq. (5) and the upper curve on the experi-

[9] See L. B. Loeb, reference 2, p. 368.

[10] See reference 1.

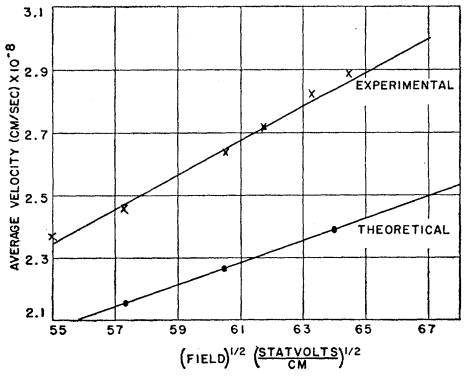

FIG. 5. Comparison of experimental and theoretical curves showing the relationship between average electron velocity and applied electric field. The experimental values are derived from a series of curves similar to those shown in Fig. 3, and the theoretical curve is determined from Eq. (5).

mental data and Eq. (4). A series of curves, similar to those shown in Fig. 3 provides the necessary experimental values. The average velocity as calculated from the electron temperature is plotted against the square root of the corresponding electric field for each case.

In comparing the two curves of Fig. 5, it is evident that the experimental data is in fairly good agreement with what one might expect on a theoretical basis. Not only does the experimental curve follow a straight line, again indicating that the gas discharge laws may be suitably applied in describing the phenomenon of field dependent secondary emission, but the slope and magnitude of the experimental curve agree well with those of the theoretical plot. This may be regarded as a check on the form of the equations used and on the value utilized for the mean free path.

IV. CONCLUSIONS

Through the use of retarding potentials it has been experimentally determined that the emitted electrons closely follow a Maxwellian energy distribution with a rather wide energy range. Then, on the basis of such a distribution, equations normally associated with gaseous discharges have been used to explain the experimental results. Furthermore, values have been obtained for the average electron energy and for the mean free path of electrons in the oxide film.

In addition, the present method provides a means of measuring the surface potentials of magnesium oxide films.

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Microwave Spectra of Tritium Iodide and Tritium Bromide*

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The $J=1\leftarrow0$ rotational transitions in TI and TBr have been observed. A tritium-deuterium mass ratio has been determined, and electronic effects which cause errors in this ratio considered.

THE microwave spectra of tritium iodide and tritium bromide have been observed by the use of a klystron-driven harmonic generator and techniques previously described.[1] The observed transitions and frequencies as well as ν_0 and eqQ are given in Table I.

Nuclear mass ratios can be determined by microwave spectroscopy from the ratio of the rotational constants, B_e, for two isotopic molecules. However, small electronic effects whose size is difficult to predict theoretically can cause small errors. In principle, these errors appear in all mass ratios determined by microwave spectroscopy, but they are particularly large for the isotopic hydrogen halides because of the large speed of rotation. This case is therefore an ideal one in which to measure the size of these errors and compare them with theoretical predictions.

TABLE I. Observed frequencies for the $J=1\leftarrow0$ transition and molecular constants of TI and TBr (Mc/sec).

	TI^{127}	TBr^{79}	TBr^{81}
$\Delta F=+1$	131 592.95±0.25	172 472.72±0.40	172 320.96±0.40
$\Delta F=0$	131 210.20±0.40	172 604.60±0.40	172 431.49±0.40
ν_0	131 501.75±0.40	172 499.10±0.40	172 343.07±0.40
eqQ	−1 822.6 ±3.0	527.6 ±2.0	442.1 ±2.0

All these small electronic effects can be represented as a single term in a perturbation calculation, but in order to estimate the size of this term it may be broken up into its components. For the hydrogen halides, the largest of these components is L-uncoupling (the excitation of higher electronic states by the rotation of the molecule).[2] Unless corrections are made for L-uncou-

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[1] Nethercot, Klein, and Townes, Phys. Rev. **86**, 798 (1952).

[2] C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy* (to be published), Chap. 8.