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Secondary Electron Emission from Metals under Positive Ion Bombardment in High Extractive Fields

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In the further study of breakdown mechanisms in high vacuum, experiments show that secondary electron emission from metals under positive hydrogen ion bombardment is small and increases only slowly with the electric field strength at the bombarded surface. Although more significant emission may yet be found with the heavier ions obtained in an actual vacuum gap, the particle interchange component of the breakdown process appears to be quantitatively inadequate on the basis of present measured electron and positive ion emission coefficients. The possible importance of negative ion emission deserves consideration in the particle exchange process.

INTRODUCTION

THE work described in this report is part of a program to study the fundamental mechanisms of electrical breakdown between metal surfaces in high vacuum. The vacuum breakdown phenomenon has been reviewed by Trump and Van de Graaff[1] and the status of the electron-ion-photon exchange theory[2] has been assessed. This theory may be stated as follows: An electron in the interelectrode space is accelerated towards the anode and on impact liberates A positive ions and C photons which travel to the cathode. On arrival each ion will liberate B electrons and each photon D electrons so that the number of electrons in the interelectrode space is now $(AB+CD)$. These coefficients are dependent primarily on the total gap voltage, the electric field at the metal surfaces, and the nature of the metal and its contaminants. If $(AB+CD)>1$, the number of electrons will multiply and breakdown will ensue. This theory satisfies the observation that positive ions of the anode material take part in the reaction,[3] and can explain the dependence of breakdown upon the total voltage between the electrodes rather than on the gradient at the cathode.

The coefficient A has been measured[1] as a function of electron energy for the case of a parallel plane steel gap, the ions being subjected to an assisting extracting electric field. This coefficient increases sharply near the breakdown voltage to about 2×10^{-3}. Hence if this AB mechanism is to be important, either the value of coefficient B must be of the order of several hundreds near the breakdown voltage, or some other particle process must be present.

EARLY WORK

Experiments conducted to determine coefficient B, i.e., number of secondary electrons emitted per positive ion from a metal surface under bombardment, by Allen,[4] Linford,[5] Hill *et al.*,[6] and Trump and Van de Graaff,[1] using in all cases a low extractive cathode field of the order of tens of volts per cm, have yielded a value from 2 to 20, the number increasing with incident ion energy. The coefficient B obtained for these small collecting fields appears to reach a limiting value at relatively low voltage gradients. It had been suggested by Trump and Van de Graaff that copious secondary electron emission might be produced in the presence of high electric fields by the impact of the relatively heavy positive ions released in actual vacuum gaps from the positive electrode and its superficial layers of absorbed gas and condensed organic vapors. Such ions would distribute a portion of the energy acquired in the interelectrode gap to the superficial layers of cathode contamination and absorbed gas and to the underlying depths from which escape of secondaries is still possible. The secondary electron emission might be expected to be strongly dependent on the molecular weight and size of the impinging ion, since these would influence the area from which emission would occur as well as the energy imparted to the emission volume. It was further suggested that the low values of coefficient B previously observed might be accounted for by space charge limitation acting during the short emission time associated with the passage of the ion through the emission depth and the subsequent dissipation of its energy by the rapid recombination and high conductivity characteristic of metal surfaces. In this event a large exponential increase of secondary electrons with electric field would be expected. Although the curves of both Hill *et al.* and Linford showed a saturation in electron emission at low collecting voltages and no sign of the $\frac{3}{2}$ exponential space charge law, it appeared reasonable that higher electric fields approaching those producing field emission might produce greatly increased current flow. The availability of a source of analyzed hydrogen ions with energies up to 250 kev afforded the opportunity of measuring coefficient B under conditions of high cathode gradient.

[1] J. G. Trump and R. J. Van de Graaff, J. Appl. Phys. 18, 327 (1947).
[2] Van Atta, Van de Graaff, and Barton, Phys. Rev. 43, 158 (1933).
[3] Anderson, Elec. Eng. 54, 1315 (1935).
[4] J. S. Allen, Phys. Rev. 55, 236 (1939).
[5] L. H. Linford, Phys. Rev. 47, 279 (1935).
[6] Hill, Buechner, Clark, and Fisk, Phys. Rev. 55, 463 (1939).

EXPERIMENTAL ARRANGEMENT

Several methods of obtaining high cathode gradients at relatively low collecting voltages were considered in order to simplify the problem of insulating two field-producing electrodes without excessive leakage between them. A sphere-plane gap with a maximum gradient of three times that existing at a parallel plane through the sphere diameter was compared with a wire and concentric cylinder arrangement. The latter was chosen since it involved a simpler system of location and insulation of the cathode with respect to the anode, since wires of various metals are more easily procured and mounted than spheres, and since with suitable ratios of radii, higher concentrations of gradient are possible. For a given collecting voltage V across this arrangement, a gradient

$$E = V/r \log_e R/r$$

exists at the wire, where R and r are the cylinder and wire radii, respectively. For example, with $r=0.1$ cm and $R=1.0$ cm, $E=4.35V$.

A section through the cylindrical bombarding chamber is shown in the drawing of the over-all experimental arrangement depicted in Fig. 1. A beam of positive ions was projected into the cylinder and impinged on the wire which was at a variable negative potential with respect to the cylinder. Those ions which did not strike the wire were collected in a Faraday cage immediately beyond the wire; the ion current to this cage was measured merely to monitor the beam and to assist its alignment with the wire. A quartz disk sealed on the bottom of the cage also facilitated positioning of the beam with respect to the wire. Both the secondary electron current from the wire to the cylinder and the ion current to the wire were measured on microammeters readable to 0.01 μA as shown in the circuit diagram of Fig. 1.

Precautions were taken by collimation to insure that none of the positive ion beam impinged on the cylinder and by the use of repressing voltage to insure that none of the secondaries from the wire escaped collection by the cylinder. Bias voltages were also applied to prevent collection of secondary electrons from the Faraday cage by the cylinder, and to avoid secondary electrons proceeded from the collimation diaphragm into the cylinder. By observing the meter currents both with and without the ion bombardment, any electrical leakage across the insulators of the wire, corona currents from connections to the cathode, back leakage through the high voltage power pack, or field emission currents from the wire were excluded in the secondary electron current e. Throughout the experiment, clean high-polished steel wires were used, out-gassing being effected both by ion bombardment and by heating electrically *in vacuo* to red heat. The vacuum was maintained at about 10^{-5} mm Hg.

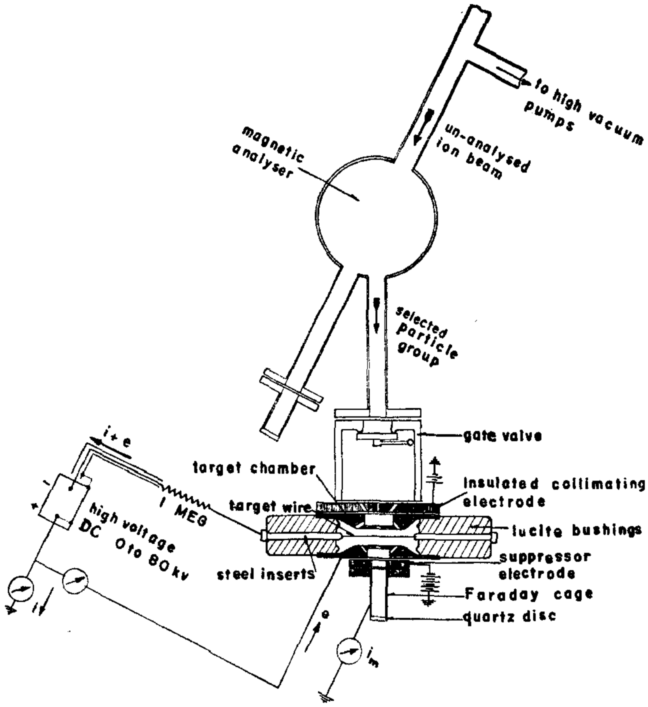

FIG. 1. Over-all experimental arrangement.

The gradient at the wire surface was varied both by change of collection voltage and by change of wire diameter. The latter was limited by the smallness of the proton current measurable and the former by the incidence of large leakage currents or even sparkover across the bushings. To facilitate changes of cathode wire without serious interference with the vacuum system a flap-type high vacuum valve was included in the pumping line immediately above the target chamber.

The positive ions were obtained from a capillary arc source using hydrogen and were accelerated to about 250 kv by means of an air-insulated electrostatic generator. Separation of protons, singly-charged hydrogen molecules, mass 3 ions, and ions of intermediate energy was accomplished by a magnetic analyzer. The analyzed ion beam currents used in this work were in the range 0.1 to 0.5 microamperes after collimation. The accelerating voltage was stabilized by a corona loading device, but this was insufficient to keep the ion current impinging on the wire cathode steady enough to permit accurate simultaneous measurements of i and e. Hence an averaging device was adopted whereby condensers were connected in parallel with the meters so as to give the same discharge time constants of several seconds for the e and i circuits. Many pairs of simultaneous current readings at practically steady state conditions were recorded for each value of extracting gradient. The coefficient $B=$ ratio e/i was determined from each pair of readings.

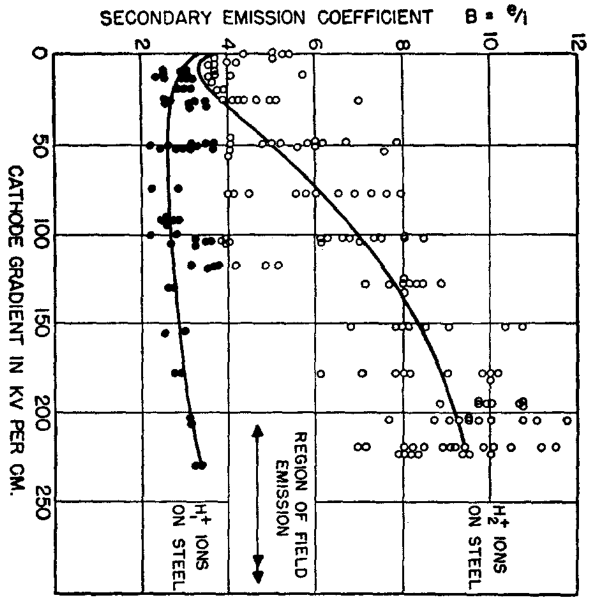

FIG. 2.

RESULTS

In Fig. 2 are plotted the series of values obtained for coefficient B for extracting gradients ranging from 0 to 200 kv/cm. Steel wires and both H_1^+ ions and H_2^+ ions were used. 200 kv/cm is the lowest gradient at which field currents were observed from the wires. The considerable spread among the individual measurements is believed to arise from the small movements of the positive ion beam and resultant variations in the angle of incidence on the target wire.

The results show a definite but slow increase in coefficient B with extracting field strength. This increase is markedly greater for H_2^+ ions than for H_1^+ ions, but never exceeds a factor of 3 and gives no indication of the large exponential dependence on field strength which had been anticipated. The coefficient B is significantly larger for the molecular hydrogen ion.

In the ion-exchange theory of electrical breakdown in high vacuum, it appears from these measurements with very light ions that field-enhanced emission of electrons by positive ion bombardment may not account in a primary way for the observed breakdown phenomena in single gaps. Further, more refined experiments are planned to extend these results. The emission properties of heavier ions such as those of nitrogen, mercury, and oil will be investigated since these are much more representative of the actual ionic particles in the vacuum gap. The possibility that accompanying negative ion emission under positive ion bombardment as observed by McKibben[7] may be the important link in this interchange will be studied.

ACKNOWLEDGMENTS

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[7] McKibben and Boyer, Bull. Am. Phys. Soc. (February, 1951).