Breakdown of Vacuum Spark Gaps

R. C. MASON
Research Laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania
(Received May 18, 1937)

Experiments with vacuum spark gaps show that the critical cathode field required for breakdown is not reduced by considerable thermionic emission from the cathode. It is concluded that positive ion emission from the anode under electron bombardment, which apparently enters at higher voltages, is not a factor up to 50 kv.

THE initiation of a self-maintained discharge in the region where the starting voltage is independent of the small density of residual gas present is usually referred to as the "breakdown of a vacuum spark gap." For the (comparatively) large current and low voltage which result on breakdown, gas must be present in far larger quantity than exists before breakdown. By the accepted theory[1] of the breakdown of vacuum spark gaps the gas results from vaporization of the anode, which is heated by electrons freed from the cold cathode by high fields. Experiments of Beams and his students,[2–4] however, with Hg cathodes to which very short time impulses were applied show breakdown occurring at fields far lower than the current theories[5] of high field emission would predict emission of electrons in amount sufficient to vaporize the anode. Either the theory of the breakdown of vacuum spark gaps, or the theory of high field emission, is incomplete.

It occurred to me that the breakdown of these spark gaps might occur through electrons freeing positive ions from the anode, as has been suggested in other connections.[6] The condition for breakdown would then be $\gamma\delta \geqq 1$, where γ represents the number of electrons liberated per positive ion striking the cathode, and δ is the number of positive ions set free from the anode by one electron; γ and δ would be expected to be functions of the total voltage but not of the field. For the discharge to start, however, at least one electron must be liberated somehow from the cathode. In some cases, a high field at the cathode might still be needed just to provide an initiatory electron, but not nearly as large a field as would be necessary to furnish enough electrons to heat the anode. If another source of electrons, ample for initiatory purposes, but not large enough to cause any appreciable heating of the anode, were present and if the breakdown voltage for different electrode separations were found, then it should be possible to test the hypothesis of positive ion emission from anodes in vacuum breakdown. The experiments described below were designed for that purpose.

EXPERIMENTAL

A 28 mil tungsten wire, bent in an approximate semi-circle of one inch diameter, was welded to two nickel leads to serve as cathode. The anode was a two inch diameter copper disk perpendicular to the plane of the cathode semi-circle, mounted on a threaded shaft so that the electrode separation could be varied by an external magnet. The tube was baked for several hours at 500°C, but no further outgassing of the metal parts was undertaken. The pressure during the experiments was always less than 10^{-4} mm.

The tungsten filament was heated by an insulated transformer. The emission current here recorded was measured with 200 volts applied to the anode; calculations show the Schottky effect increased the emission by not more than a factor of 10 at the highest fields used.

Voltage was applied to the tube from a 1/16 microfarad condenser bank through a 6000 ohm resistance. The condensers were charged by a full wave rectifier. Starting from a low value, the

[1] Hull and Burger, Phys. Rev. **31**, 1121 (1928); Snoddy, Phys. Rev. **37**, 1678 (1931).
[2] Beams, Phys. Rev. **44**, 803 (1934).
[3] Quarles, Phys. Rev. **48**, 260 (1935).
[4] Moore, Phys. Rev. **50**, 344 (1936).
[5] Fowler and Nordheim, Proc. Roy. Soc. **A119**, 173 (1928); Stern, Gossling and Fowler, Proc. Roy. Soc. **A124**, 699 (1929).
[6] Van Atta, Van de Graaf and Barton, Phys. Rev. **43**, 158 (1933).

voltage between the electrodes was raised slowly, over several seconds, by means of a regulator in the primary of the supply transformer, until breakdown occurred. The breakdown voltage was obtained by reading the primary voltage, which in turn was calibrated directly against a standard spark gap in air in the rectified output. Breakdown was obtained for cathode cold and for 0.04 microamp. and 7.0 microamp. emission, with separations from 0.013 to 0.12 cm between the anode and the closest point of the cathode filament.

Results

The breakdown voltages are plotted against electrode separation in Fig. 1. At each point, the vertical line connects the highest and lowest voltages obtained in that particular series of tests, while the horizontal dash marks the average breakdown voltage of the series. The breakdown voltage gradually increased with testing; the higher points shown for certain separations were gotten after the lower points, with some intervening breakdowns.

The curve in Fig. 1 shows the voltage necessary to give a constant field at the cathode of 600 kv per cm (calculated on the assumption that the electrodes consisted of an infinite plane and infinite parallel cylinder).

Most of the points for cathode cold fall very well along the curve. Even with ample initiatory electrons, the breakdown voltage certainly increases with increasing separation, in such a way as to maintain approximately constant cathode field. When the cathode is heated, actually somewhat higher voltage seems to be required than when no electron emission occurs. The experiments, then, fail to show any evidence for emission of positive ions by electron bombardment up to 50 kv. Anderson[7] found for very large electrode separation, requiring up to 500 kv for breakdown, the breakdown voltage increased less rapidly than the electrode separation, so the cathode field required continually decreased from 800 kv per cm at 80 kv to less than 50 kv per cm at 500 kv. He attributed the reduction of gradient to positive ion emission from the anode, but his experiments are not conclusive enough to show that the effect on breakdown is simply that postulated above.

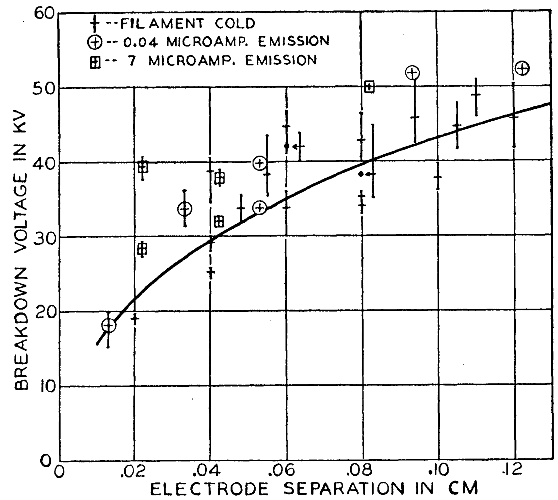

FIG. 1. Breakdown voltage *vs.* electrode separation, with cathode cold and with cathode heated to give different electron emission (measured at 200 volts). Solid curve shows voltage necessary to produce a constant field of 600 kv per cm at the cathode.

Some experiments with aluminum electrodes, which had a breakdown gradient of about 300 kv per cm for steady applied voltage, were performed with an impulse voltage which rose to 60 kv crest in 1.5 microseconds. For a given separation, the breakdown voltage, measured by cathode-ray oscillograms, was much higher for the impulse than for the steady voltage. A probable explanation is that no electrons were emitted until a critical field was reached; then, the supply voltage continued to rise above this d.c. breakdown voltage during the time required for vapor from the anode to reach the cathode. A few tests for separations from 0.02 to 0.07 cm may be explained in this way if the vapor velocity is about 10^5 cm per sec.

[7] Anderson, Trans. A. I. E. E. **54**, 1315 (1935).