The Formation of Metallic Bridges Between Separated Contacts*

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Low resistance bridges were formed between gold, steel and carbon electrodes having separations of $2-70\times 10^{-6}$ cm by applying voltages less than the minimum sparking potential. For a given pair of electrodes the field required to form the bridges is a constant and is $5-16\times 10^{6}$ volts per centimeter. Measurements of the temperature coefficient of resistance of the bridges identify them as consisting of the material of the electrodes. A study of their resistance as a function of the displacement of one of the electrodes shows that they may be pulled out as well as crushed. At voltages less than those required to form the bridges, field currents exist. These increase rapidly as the field is raised and attain a value around 10^{-10} ampere before the bridges are formed. Calculation of the maximum electrostatic stress on the electrodes at the time of breakdown gives a value 0.05 to 0.0005 times the tensile strength of the electrode material at room temperature. The field is locally higher than that calculated because of surface roughness and the tensile strength is probably lowered by the local heating known to accompany field currents. The data therefore indicate that electrostatic force pulls material from the electrodes to bridge the gap.

THE study of the passage of electric current across small gaps is an old problem, having been investigated by Wood,[1] Earhart,[2] Kinsley,[3] and Hobbs[4] as early as 1900. The results of these early experiments were uncertain, especially those pertaining to the breakdown of the gap at high field strengths. Around 1920 the subject was again investigated by Rother,[5] Hoffman[6] and Rohmann[7] in connection with their study of cold point discharge. These investigators were chiefly interested in the passage of current between separated contacts. The present paper presents data showing that low resistance bridges are formed between separated metallic electrodes at fields of about ten million volts per centimeter and that the material of the bridge is that of the electrodes.

The measurements were made with a displacement device in which the contact could be rigidly fixed and manipulated at will. This apparatus,[8] shown in Fig. 1, consists essentially of a cantilever bar A cut from a solid block of steel and so arranged that motions applied through a calibrated screw B, can be reduced in accordance with the theory of the cantilever bar, by a factor of 300 to 1 when applied to the rod D pivoted near its base. The two contact electrodes C_1 and C_2 are mounted as shown. Rough motions can be obtained by means of the screw F, and stiff springs E and G eliminate any slack motions. With this apparatus contact movements as small as 1×10^{-7} centimeters can be produced and measured.

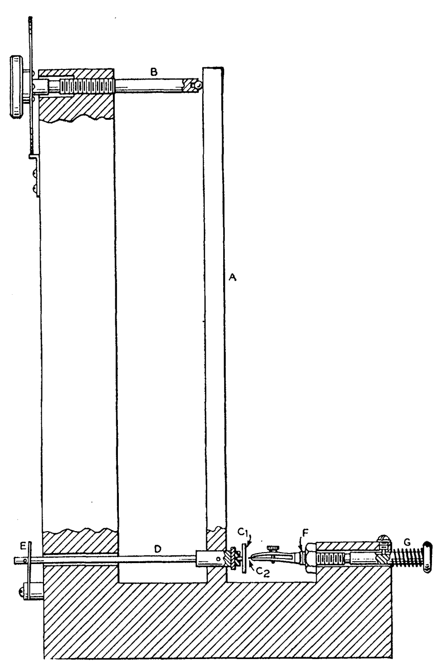

FIG. 1. Cross-section diagram of a cantilever bar device for controlling and measuring small contact displacements.

* Presented orally at the American Physical Society meeting held in Washington, D. C., April 29 to May 1, 1937, G. L. Pearson, Phys. Rev. **51**, 1015(A) (1937).

[1] R. W. Wood, Phys. Rev. (I), **5**, 1 (1897).

[2] R. F. Earhart, Phil. Mag. **1**, 147 (1901); Phil. Mag. **16**, 147 (1908).

[3] C. Kinsley, Phil. Mag. **9**, 692 (1905).

[4] G. M. Hobbs, Phil. Mag. **10**, 617 (1905).

[5] F. Rother, Physik. Zeits. **23**, 423 (1922); Ann. d. Physik **81**, 317 (1926).

[6] G. Hoffman, Zeits. f. Physik **4**, 363 (1921).

[7] H. Rohmann, Zeits. f. Physik **31**, 311 (1925).

[8] Previously described by C. J. Christensen and G. L. Pearson, Bell Sys. Tech. J. **15**, 197 (1936).

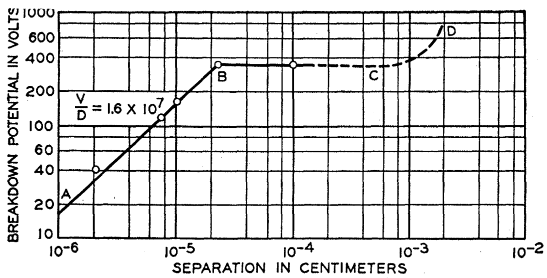

FIG. 2. Breakdown potential as a function of separation for gold electrodes in air at atmospheric pressure.

The contact electrodes used in these measurements were spheres of gold, steel and carbon. The gold electrodes were made by evaporation of the metal on glass spheres having a diameter of three sixteenths inches. This method was used since it gives a smoother surface than that obtained by other methods. The steel electrodes were standard one-quarter inch SKF ball bearings and the carbon electrodes were imported French carbon spheres one-sixteenth inch in diameter. After mounting a pair of spheres in the cantilever bar device (sometimes one sphere and a disk was used as shown in Fig. 1), the following procedure was used for studying the formation and properties of metallic bridges. The point of zero displacement was taken as that at which electrical contact is first established on bringing the electrodes together with a small voltage such as one-tenth volt in the circuit. The electrodes were then separated a known distance and the voltage in the circuit slowly raised until at a definite voltage, depending on the contact separation, a breakdown occurred. When this happened the resistance dropped permanently to a small part of an ohm. Before repeating the experiment the electrodes were rotated so that a clean surface was again obtained. This procedure gave fairly reproducible results as shown by the typical examples discussed below.

Figure 2 shows the results of a series of measurements made with the gold electrodes in air at atmospheric pressure. The abscissae represent separation in centimeters and the ordinates breakdown voltages, both scales being logarithmic. This curve has the same features as those obtained by the early investigators.[2–4] In the region AB breakdown occurs at voltages less than the minimum sparking potential for air, which is about 350 volts at atmospheric pressure. Here the breakdown voltage is directly proportional to the contact separation and the maximum field is 16 million volts per centimeter. In this region a low resistance bridge is always formed between the electrodes at breakdown. In the region to the right of B, a gas discharge occurs at or above the minimum sparking potential in accordance with Paschen's law and no low resistance bridge is ever formed. Over the horizontal portion BC discharge occurs between portions of the spherical electrodes which are at the minimum sparking distance, 6×10^{-4} cm. To the right of C the minimum separation becomes greater than this distance and the discharge voltages therefore increase. Experiments performed on gold spheres in air at pressures less than atmospheric gave low resistance bridges at the same maximum field over the region AB. The discharge voltages in the region BCD, however, depended upon the pressure.

Curves similar to that given in Fig. 2 were obtained for the steel and the carbon electrodes except that breakdown in the region AB occurred at a field of about 5 million volts per centimeter. This lower value is probably due to the fact that these electrodes had surface roughnesses which produced local fields greater than that measured. It should be pointed out that the maximum field strength of 16 million volts per centimeter observed here is greater, by a factor of 8, than those which the best solid dielectrics are known to withstand.

The results of a series of resistance *versus* displacement measurements made on a single contact formed between steel ball bearings are

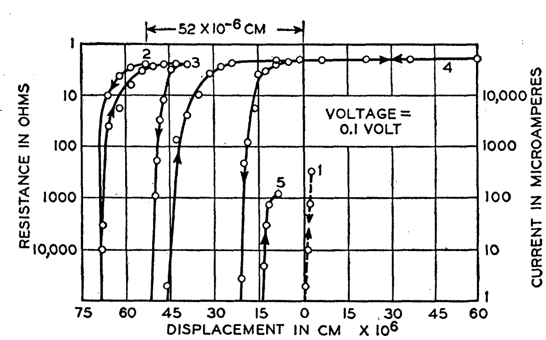

FIG. 3. The effect of tension and compression on a bridge formed between steel electrodes.

[9] A. von Hippel, J. App. Phys. 8, 815 (1937).

shown in Fig. 3. After determining the zero point, as shown by the dotted line, the contacts were separated (to the left in the figure) 52×10^{-6} centimeter and the voltage slowly increased until at 260 volts, which corresponds to a field of 5 million volts per centimeter, a breakdown occurred. The resistance as indicated at (2) was then about 2 ohms when measured with 0.1 volt. (This is mainly circuit resistance as the bridge resistance was approximately 10^{-4} ohm). Further separation pulled out the contact and finally broke it after it was extended about 20×10^{-6} centimeter. The same contact was then remade and under compression returned to its original resistance at (3). Extension broke it again and compression reestablished it and so forth as shown at (4) and (5). This behavior suggests a bridge of metal which extends and breaks in tension and which is crushed in compression.

In order to examine the nature of the material forming these bridges a series of measurements was made to find the effect of temperature on their resistance. By means of a technique developed in the study of the carbon microphone,[10] several different voltages were applied to the electrodes and the resulting bridge resistance measured. From contact theory it is known that the rise in temperature of a short thick bridge is proportional to the square of the applied voltage. When steel electrodes were used the bridge resistance increased with increase in voltage thus indicating a positive temperature coefficient. With carbon electrodes the bridge resistance decreased with increase in voltage. These results indicate that the temperature coefficient of the bridge has the same sign as that of the electrode material.

To confirm this viewpoint Mr. E. J. Ryder of these Laboratories, working with apparatus[11] developed for studying relay contacts, very kindly made a careful quantitative measurement of the temperature coefficient of resistance of a bridge formed between gold electrodes. In this work the temperature was controlled externally by means of a furnace. The measured value of α at room temperatures was 0.0028 in the low resistance bridge while that in a solid gold rod was 0.0034. The small difference between the two values may be attributed to impurities which enter the bridge at breakdown. Furthermore, Ryder measured the breaking strength of the gold bridge and from this calculated the cross-sectional area and the resistance, the latter being in good agreement with the measured resistance. The definite conclusion to be drawn from these experiments is that the bridges are formed from the electrode material.

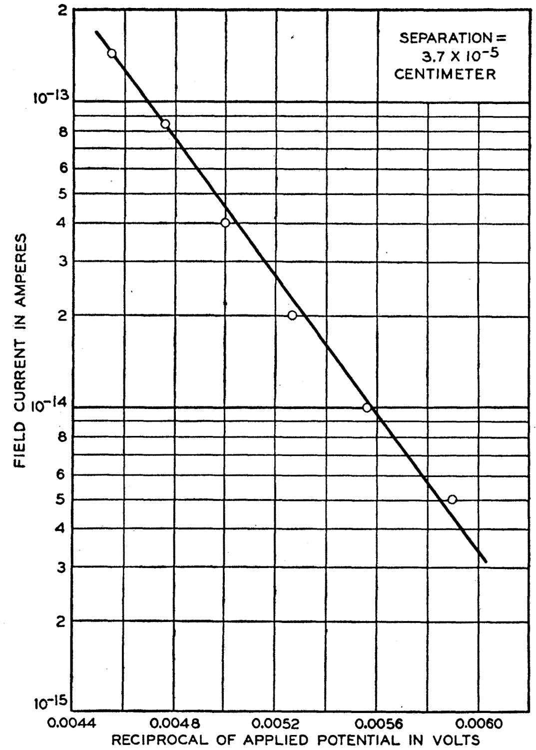

FIG. 4. Field emission current between steel electrodes separated 3.7×10^{-5} centimeter.

At fields around a million volts per centimeter field currents are known to exist.[5–7] Accordingly, an electrometer tube circuit was set up to see if such currents could be detected before the bridge was formed. Although this current proved too small to be measured at low voltages, it increased rapidly with increase in the field and attained a value around 1×10^{-10} ampere before the bridge was formed. Fig. 4 shows the current *versus* voltage relationship for steel balls separated 3.7×10^{-5} centimeter. The ordinates represent the current in amperes plotted logarithmically and the abscissae represent the reciprocal of the applied voltage. The straight line relationship

[10] F. S. Goucher, Bell Sys. Tech. J. **13**, 163 (1934).
[11] Bell Lab. Record **16**, 374 (1938).

obtained by this method of plotting identifies the current between the electrodes before breakdown as due to field emission. This curve is reversible if the voltage is not raised so high that a bridge is formed.

Since the radii of curvature of all the electrodes used in these measurements are large in comparison with their separation the electrostatic forces involved can be calculated by means of the following parallel plate equation:

$$F = 4.42\times 10^{-7}\epsilon (V/d)^2 A,$$

where F is the force in dynes, V the voltage, d the separation in centimeters, A the area in square centimeters, and ϵ is the dielectric constant which is 1 for air. For the gold spheres this force is 1.1×10^8 dynes per square centimeter at the time the bridge is formed. The tensile strength of gold is about 2.5×10^9 dynes per square centimeter which is larger by a factor of about 20. For the steel electrodes the calculated electrostatic force and tensile strength are, respectively, 1×10^7 and 2×10^{10} dynes per square centimeter. Differences of this order of magnitude are to be expected since local increases of stress are known to exist because of surface roughness[12] and local heating of the field currents produce softening of the metal electrodes.

It is reasonable to conclude, therefore, that the bridges formed in separated contacts at voltages below the minimum sparking potential are the result of pulling metal from the electrodes by electrostatic force.[13]

In conclusion I wish to thank Dr. J. B. Johnson and Dr. F. S. Goucher for many helpful discussions during the preparation of this paper.

[12] Data of other workers studying field emission from tungsten and molybdenum wires in vacuum indicate that local fields due to roughness may be from 20 to 200 times the average: A. J. Ahearn, Phys. Rev. **44**, 277 (1933).

[13] A somewhat similar type of rupture of the electrodes was observed by A. J. Ahearn (Phys. Rev. **50**, 238 (1936)), while studying field emission from fine wires in a vacuum. In explanation of large increases of current at critical values of applied voltage he suggested a rupturing of the surface where, because of roughnesses the electrostatic force exceeded the tensile strength of the material.

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Turbulence in Convection in Gases Between Concentric Vertical Cylinders

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In a thermal diffusion apparatus consisting of two concentric vertical metal cylinders the temperature of the inner hot cylinder is measured for constant power input in the heater as a function of the pressure of the contained gas (N_2 or CO_2). The change from lamellar convection flow to turbulence produces sharply at a certain pressure a cooling which increases with further rise in the gas density. For this critical density the ratio of the remixing by convection to that by diffusion as well as the Reynolds numbers are computed. The latter are around 150; i.e., about $\frac{1}{10}$ the values found for flow through pipes. With increasing temperature difference a minimum value of the pressure for onset of turbulence is found. In order to insure lamellar convection flow in isotope separation by thermal diffusion, conditions should be adjusted so that the ratio of the two remixing effects is not more than $\frac{1}{10}$ these critical values.

In the discussion of experiments on the separation of isotopes by thermal diffusion, such as those reported by Clusius and Dickel[1] and by Brewer and Bramley,[2] it has been considered that the convection flow in the gas is lamellar.[3] The gas is confined in the gap space a few millimeters in width between two vertical surfaces, one of which is hot. For such a case, as shown in reference 3, the Reynolds number is

[1] K. Clusius and G. Dickel, Naturwiss. **26**, 546 (1938); **27**, 148 (1939).

[2] A. K. Brewer and A. Bramley, Phys. Rev. **55**, 590 (A) (1939).

[3] W. H. Furry, R. C. Jones and L. Onsager, Phys. Rev. **55**, 1083 (1939).