Experiments on the Initiation of Electric Arcs

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Arcs have been struck in vacuum between widely spaced electrodes by positive ion charging of an insulating film on the cathode, at separations from 0.5 to 5 mm and at potentials from 34 to 2000 volts. The arc current must be allowed to grow initially at the rate of at least 10^6 amp./sec. for the arc to occur. These experiments constitute a test of one of the fundamental steps postulated to account for the initiation of an arc between electrodes coming together at low voltages.

I. INTRODUCTION

WHEN two electrodes are brought together to complete an electrical circuit, under some conditions an arc is formed between them before they make metallic contact.[1] A series of events by which this arc can be initiated has been postulated,[1] one step of this series being the emission of electrons due to the intense field across an insulating film on the cathode produced by positive ions resting on this film. This paper is an account of experiments to test this step in the development of the arc; specifically, to study conditions under which an arc can result from the field produced across an insulating film by positive ions resting on it.

For a normal arc,[2] Druyvesteyn[3] has suggested that *insulating material* on the cathode may become so highly charged with positive ions that electrons are drawn from the cathode by the high electric field which they produce. Langmiur[4] suggested this mechanism earlier as an explanation of "flash back" during the reverse cycle of mercury vapor rectifiers. This was studied in detail by Kingdon and Lawton.[5] A similar effect has been reported for other types of discharge by Guntherschulze[6] in the "Spritzentladung" of the glow discharge, in the Malter[7] effect, and by Paetow.[8] The "scintillations" described by Koller and Johnson[9] in experiments with Malter cathodes were probably minute arcs.

In the experiments reported in this paper insulating films are deposited on an electrode by exposure to organic vapors, or films are built up one layer of molecules at a time from monomolecular layers of barium stearate by the Langmuir-Blodgett[10] technique. By using a positive ion gun to charge up these films, arcs have been produced between electrodes at various separations from 0.5 to 5 mm at initiating potentials as low as 34 volts, when, without the positive ions, no breakdown occurs up to 6000 volts. Current densities greater than 10^6 amp./cm^2 have been observed.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement. The circuit in which the arc discharge is observed consists of the condenser C, the inductance L, and the electrodes. The cathode consists, in most experiments, of a highly polished chromium plated brass plate, on which are deposited the various insulating films. The anode is a platinum rod with a hole drilled along its axis, and is mounted in the end of an ion gun with the hole serving as a window through which positive ions are directed to the cathode. The ion gun consists simply of a thermionic filament, a positive grid for accelerating the electrons which ionize gas molecules, and the electrode with the window. The circuit is mounted inside a chamber which can be evacuated. The cathode plate is perpendicular to the gun axis and can be rotated in its own plane about an axis offset from the gun axis, so that as the insulating film is damaged by the arcs it can be replaced by fresh film. Positive ion current passing through the anode and reaching the cathode is observed by the galvanometer.

The apparatus is operated with the chamber at a pressure of about 5×10^{-3} mm Hg, which is sufficiently low to prevent gas discharges and yet high enough to provide plenty of positive ions. The mean free path of the gas atoms at this pressure is about 1.0 cm. The anode to cathode separation is in the range 0.5 to 5 mm. When an arc occurs it draws charge from the condenser and charges it in the opposite direction during a half-period of the circuit. When the current reaches zero at

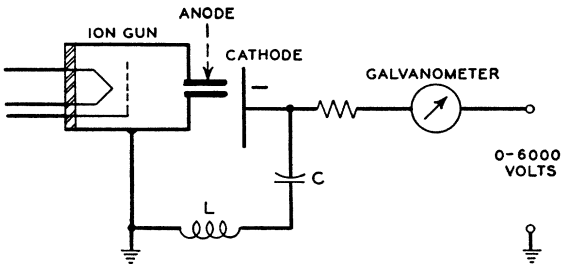

FIG. 1. Experimental circuit.

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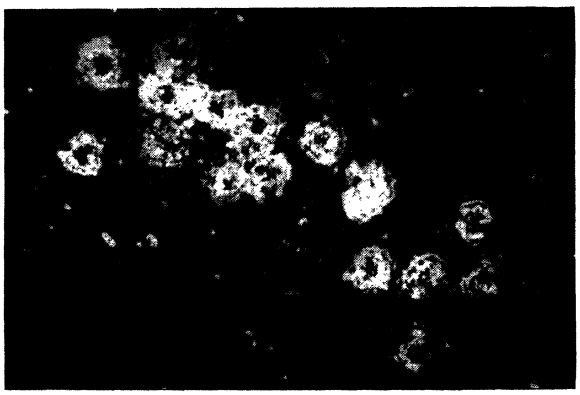


FIG. 2. Photograph of the damage to a 200-layer barium stearate film by a succession of arcs at an applied voltage of 700.×350. (The damaged spots produced by arcs at applied voltages of 200, Table I, are much smaller.)

the end of the half-period the arc stops. The condenser is immediately recharged, causing a ballistic swing of the galvanometer. The galvanometer thus serves two purposes—giving the steady value positive ion current, and, from the gallistic throw, the charge passed through each arc. The arc is completed before any appreciable recharge since the time constant of the charging circuit is about a thousand times as great as the maximum arcing time.

The occurrence of an arc is noted either by visual observation of the bright flash between the electrodes, by the galvanometer swing on recharging, or on the trace of an oscilloscope connected directly across the electrodes.

III. RESULTS

Experiments have been carried out on insulating films prepared in a number of different ways. Discharges have been found to occur at various low applied voltages after the metal electrodes had been exposed to vapors of turpentine, varnoline, or α-limonene, or after the cathode had been dusted with fine MgO powder. Discharges occur also when the cathode is of carbon rather than metal, but experiments with a carbon cathode have been found to be very erratic. The most reproducible experiments have been carried out with a cathode coated with barium stearate films deposited one layer of molecules at a time by the Langmuir-Blodgett technique,[10] and all of the work reported below refers to experiments upon such films. *In no case does a discharge occur when the cathode is a relatively clean metal surface nor in the absence of a current of positive ions*, at least for applied potential differences below about 6000 volts.

In experiments with barium stearate films no discharges are obtained unless the film thickness is greater than 10^{-5} cm, and discharges are more frequent for the thicker films up to 5.4×10^{-5} cm (200 monomolecular layers) which have been the thickest films studied. When a new film is bombarded by positive ions, discharges occur at irregular and progressively increasing intervals until they finally cease completely. The positive ion current which causes the discharges has been of the order of 10^{-8} amp., but no clear dependence of the frequency of discharge on the magnitude of the current has been established. The frequency of discharge has been found to increase with increasing voltage in the range from 34 to 700 volts but it is not clear that the frequency depends upon the electrode separation in the range which has been investigated between 0.5 and 5 mm.

Figure 2 is a photo-micrograph of the damage done by a number of discharges to a 200-layer film. Each spot of this photograph is caused by a discharge breaking down the film. The group consists of all the breakdowns occurring at one position of the cathode. When the barium stearate is removed from a damaged electrode by dissolving it in acetone, the surface of the chromium under each spot is found to be chewed up and pitted.

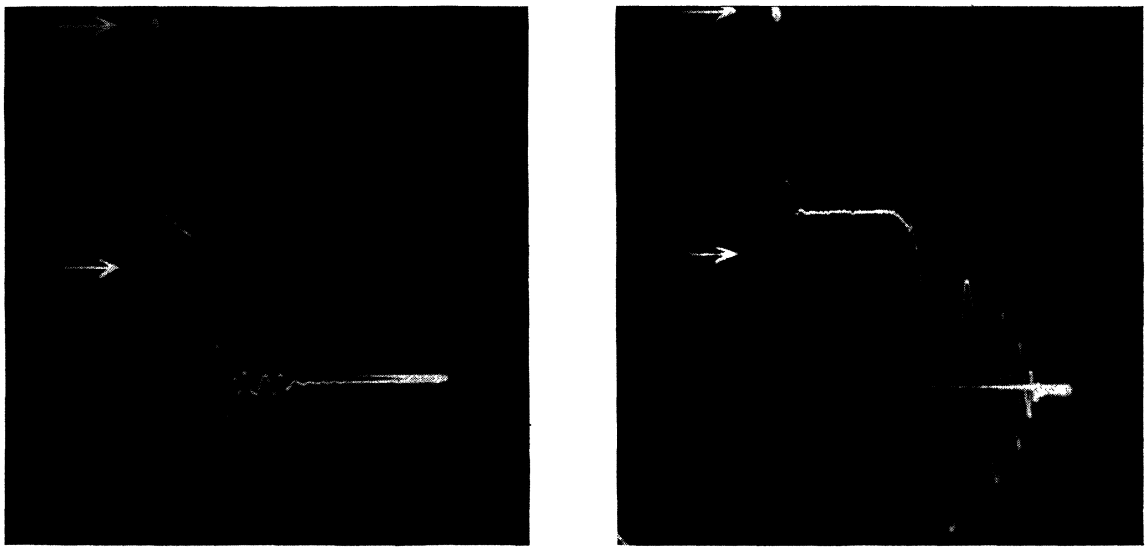
The photograph of Fig. 2 was obtained after arcs at an applied voltage of 700. After arcs at 200 volts the damaged spots have cross-sectional areas more than five times smaller than those of this photograph. From these areas it has been calculated that the maximum current densities in arcs at 200 volts and at the lower inductance are above 10^6 amp./cm^2 and may be above 10^7.

By means of a high resolution oscilloscope it has been determined that the discharges are actually arcs. Figure 3 shows photographs of oscilloscope traces for two values of inductance, keeping the other parameters the same. The calculated half-periods of the circuit are 0.26×10^{-6} sec. for 3(a) and 0.98×10^{-6} sec. for 3(b), which agree with the arc durations as measured on the traces of Fig. 3 within the accuracy with which the sweep time is known.

At each discharge the voltage drops abruptly from its initial value (indicated on the photographs of Fig. 3, for example, by the bright spots and the upper arrows) to the arc voltage, and at the end of the arc to a negative value, as shown in Fig. 3 by the horizontal retrace lines. The positions of zero voltage are indicated on the photographs by the lower arrows. Measured arc voltages and final voltages averaged from 52 oscilloscope traces are given in Table I.

During each arc at the lower inductance the arc voltage was steadily decreasing and the measured value of the table was the approximate mean. In each arc at the higher inductance there was an initial high voltage lasting on the average 0.11×10^{-6} sec., followed by the main arc at a comparatively constant voltage. The resistances given in the sixth column of Table I are the high frequency resistances calculated from the applied, arc, and final potentials.[11]

[11] See Eq. (4), page 1094 of reference 1.



(a) (b)

FIG. 3. Oscilloscope traces of electrode potential during arcing. $V_0=200$ volts, $C=2\times10^{-9}$ f, electrode separation 1 mm, sweep time 2×10^{-6} sec. The 200-volt applied potential makes the spot at upper left, marked by the upper arrows; the positions of zero potential are marked by the lower arrows. (The open circuit oscillations occurring after the end of the arc are of no interest in the present investigation. The horizontal line represents the path of the oscilloscope spot on its return trace.)

(a) $L=3.3\times10^{-6}$ hr. The arc potential averages 33 volts.
(b) $L=48.3\times10^{-6}$ hr. The arc has two stages, the first at 60 volts, then the main arc at 34 volts.

Each of the two series of measurements of Table I was made on a new film of barium stearate. The *initial* arc voltage at the higher inductance (column 2) varies considerably between different observations, in general becoming steadily higher throughout the course of a series of observations; the voltages represented by the numbers of columns 3, 4, and 5 remain substantially unchanged for different arcs of a single series. It was also observed that the frequency of the discharges decreases with successive measurements on a single film until no arcs can be obtained *even from areas which have not been used.* The increase in initiating arc potentials (column 2) thus probably results from a progressive change in the insulating layer caused by the action of the positive ions. The initial arc potentials seem to be determined by the insulating layer, while the main arc potentials (columns 3 and 4) are characteristic of the metal only.

Calculations of the transit times across the gap for ions and vapor molecules lead to some interesting considerations. The transit time for air ions across the 1 mm gap of the arcs of Fig. 3 and Table I is 0.09×10^{-6} sec., which is nearly the same as the duration of the initial arc (0.11×10^{-6} sec.), suggesting that the initial arc lasts until the arrival of positive ions obtained from adsorbed gas on the anode. The transit time for platinum ions from the anode is 0.23×10^{-6} sec. The transit time for platinum vapor atoms at the boiling point of platinum (4300°C) is 1.6×10^{-6} sec., for chromium atoms from the cathode 1.1×10^{-6} sec., and for any vaporized atoms or molecules from the insulating layer perhaps about the same. Since the whole period of the arc is shorter than these vapor transit times, the observations apparently rule out any process which requires the filling of the gap by vaporization from the electrodes.

This conclusion is supported by visual observation of the arc, for there is a visible discharge only very close to the electrodes. A concentrated, brilliant flash occurs at the cathode, and at the smaller gaps a duller, diffuse glow at the anode. At 1 mm these occupy perhaps a quarter of the gap length. At 2 mm the anode glow has faded out, leaving the tiny cathode flash extending less than a tenth of the way across.

If the inductance L of the circuit is increased a value is soon reached for which the arc will not occur. This value varies with the applied voltage V_0, and a series of measurements was made in which, for each value of L, V_0 was slowly increased until the first arc occurred. It was found that above the arc voltage, v, this minimum V_0 increases approximately linearly with L, thus making $(V_0-v)/L$ nearly constant. Since in the arc the initial rate of increase of current $(dI/dt)_{t=0}$ is also equal to $(V_0-v)/L$ the data indicate that for an arc to form a minimum value of that rate is required. From the data this minimum value is 10^6 amp./sec.

With $L=48.3\times10^{-6}$ hr. and $C=2\times10^{-9}$ f, oscilloscope observations have been made at values of V_0 as high as 400 and as low as 100. In this range there is no change in the voltage of the main arc. At 100 volts the arcs occur very infrequently and calculation shows that

TABLE I. Averages of measurements from oscilloscope records.

Applied potential 200 volts $C=2\times10^{-9}$ f Electrode separation 1 mm							
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Inductance	Arc voltage Initial	Mean	Main	Final voltage	Circuit res.	Max. current	Max. current density
(10^{-6} h)					(ohms)	(amp.)	(amp./cm^2)
3.3		33.5		− 98	6	4.0	4×10^6
48.3	76		37	−109	12	1.0	1×10^6

the initial rate of current increase is only slightly greater than the above value of 10^6 amp./sec.

In these arcs it is of course necessary that there be enough positive ions produced to prevent space charge limitation of the current density. Langmuir[12] has shown that ions produced at the anode can increase the maximum current density by a factor of only 1.8, so that ions must be supplied by ionization of the residual gas. For an arc like that of Fig. 3(b) (1 amp. maximum current, 1×10^{-6} sec. duration, and 5×10^{-3} mm Hg pressure) calculations indicate that the number of molecules entering the electron stream, assuming it to have the same breadth as the cathode spot, is of about the right size to provide sufficient ionization. At higher applied voltages and lower inductances, however, arcs have been produced with maximum currents much larger and lasting much shorter times, and it appears that the ionization produced (if the electron stream is no larger than the cathode spot) is orders of magnitude too small. Perhaps the arc can start at small current, small diameter, and high voltage, and then expand rapidly in size and current, with a rapidly decreasing voltage. Some evidence supporting this theory is found in Fig. 3(a), which shows the arc voltage decreasing throughout the arc's lifetime.

During the course of this work the author received many valuable suggestions from L. H. Germer, to whom he expresses sincere thanks.

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On the Symmetry of Graphite

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X-ray diffraction evidence indicates that the symmetry of graphite can be no higher than twofold. Evidence consists of twin observations and the occurrence of satellite reflections, both of which are incompatible with sixfold symmetry. Both phenomena strongly suggest that the classical concept of equivalent carbon-carbon bonds must be discarded in favor of one involving unequal bond lengths and bond angles.

I. INTRODUCTION

RECENTLY, considerable interest has been shown in the conductivity and the band structure of graphite.[1–4] The theoretical studies and calculations have been based on the classical crystal structure determined by Bernal,[5] where the symmetry is considered to be hexagonal holohedral. The structure consists of planar sheets of carbon atoms arranged in equilateral and equiangular hexagonal rings. The atoms in the planes are separated by a distance of $1.42kx$ units and the planes by $3.348kx$. Hexagonal symmetry is consistent with early x-ray diffraction studies and with most morphological examinations. Goldschmidt,[6] however, depicts a crystal which can have no higher than twofold symmetry. This is an isolated example and, apparently, has been regarded as a curiosity. Recently, Hoerni, and Weigle[7] have described extra reflections in electron diffraction patterns, which appear to double the a-axis. Finally, Pauling and the writer[8] have presented evidence based on certain twin relations which indicate a symmetry lower than hexagonal. It is the purpose of this communication to discuss this evidence and some of its implications, as well as to outline recently obtained x-ray diffraction data which appear to demonstrate conclusively that the symmetry of graphite cannot be higher than twofold. Although the study is not complete, it is felt that publication of the preliminary data is warranted because of its possible influence on theoretical studies.

II. TWIN OBSERVATIONS

Weissenberg and precession photographs, rotation and precession about the c-axis, have been taken of some hundred or more graphite crystals. These include

* The Knolls Atomic Power Laboratory is operated by the General Electric Company for the AEC.

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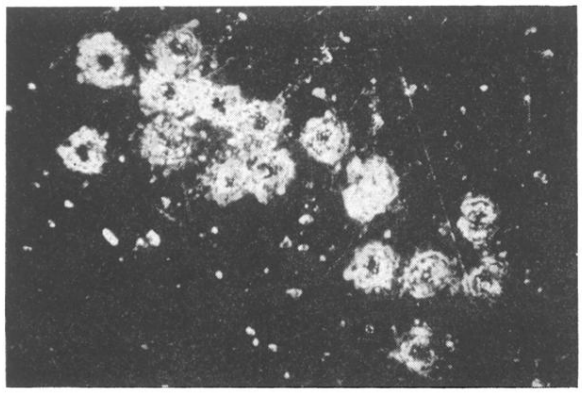

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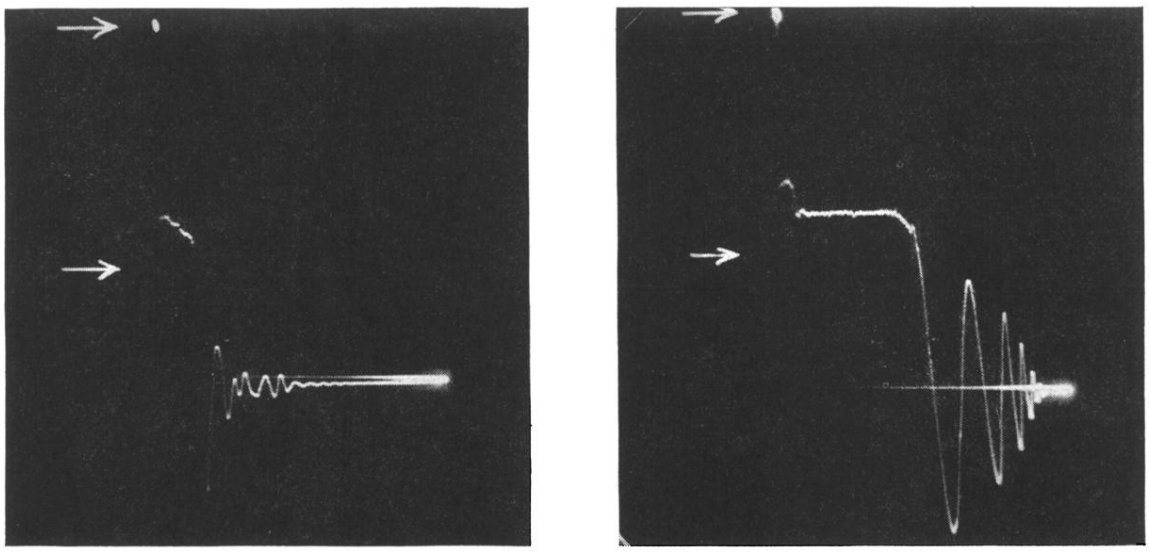

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