THE DEVELOPMENT OF SPARK DISCHARGES IN HYDROGEN

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Summary

Streak photography has been used to supplement the earlier shutter photographic investigation of Doran and Meyer (1967) using the same coaxial cable discharge circuit. Additional information has also been obtained from measurement of the potential distribution between the electrodes at two stages in the spark development. Redistribution of space charge is shown to give rise firstly to a transient diffuse glow discharge that has a close similarity with a normal d.c. glow discharge. It has also been shown that, even while the diffuse glow discharge expands, a partial constriction occurs in which most of the current flows along a narrow axial column. The resulting maximum in electron density eventually causes a rapid increase in dissociation of molecular hydrogen on the axis of the discharge brought about by a rise in the gas temperature. Owing to its greater electrical conductivity this axial column soon carries the entire current and the discharge becomes filamentary though still being maintained by a high cathode fall field, which exists until a sudden change in the cathode mechanism gives rise to the low voltage arc channel. Both the filamentary glow and arc columns are observed to expand according to an $r \propto t^{\frac{1}{2}}$ law.

I. INTRODUCTION

There exist two apparently different mechanisms by which a spark channel may be formed in a gas at high pressures, depending, amongst other things, on the magnitude of the overvoltage applied to the discharge gap (cf. Raether 1964). At low overvoltages (a few per cent), with which the present investigation is mainly concerned, the discharge starts with several generations of electron avalanches that lead firstly to the formation of a diffuse glow discharge and finally to a filamentary conducting path between the electrodes. Precisely how this filamentary path is formed is still not completely understood.

Doran and Meyer (1967), investigating sparks in hydrogen produced by the discharge of a coaxial cable, observed two quasi-stable phases of the discharge before the final arc channel was formed. The first of these resembled in appearance a diffuse high pressure glow discharge, exhibiting a uniform positive column, a Faraday dark space, and a bright negative glow covering a wide area of the cathode. After a short time a transition occurred to a further glow discharge having the above distinct regions, but in which the positive column appeared filamentary. Finally a bright luminous region rapidly developed close to the cathode accompanied by the collapse of voltage to a value typical of an arc discharge. All these phenomena occur within 300 nsec of the initiation of the discharge.

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In the present investigation these phases of development have been studied in some detail by means of highly time-resolved streak and shutter photography using an image converter–intensifier camera system. These techniques have provided additional information on the processes that lead to the development of a filamentary spark channel in hydrogen and have also allowed a more detailed study of one phase of the spark development, namely, the transient diffuse glow.

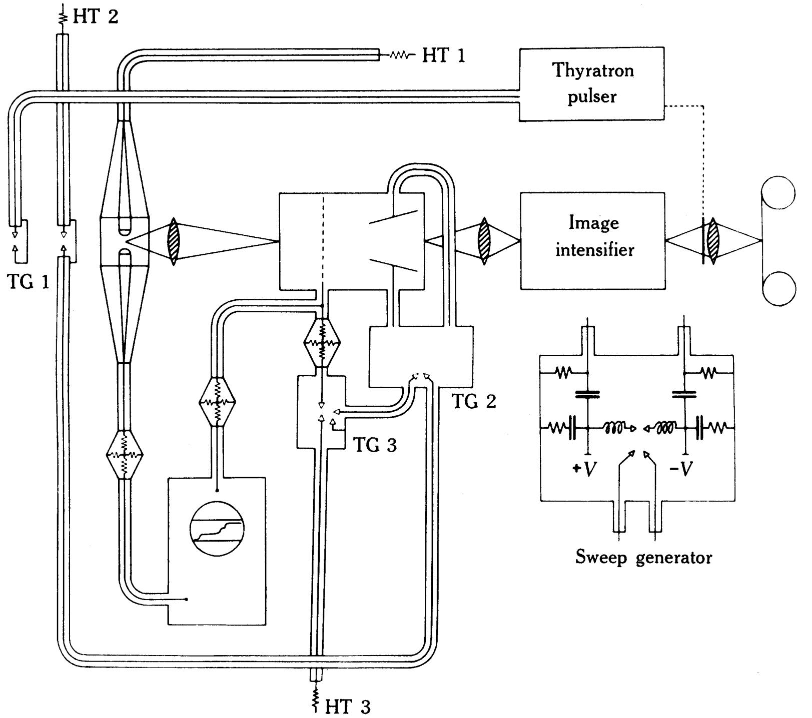

Fig. 1.—Experimental arrangement for producing both streak and shutter photographs of the spark discharge.

II. Apparatus

Sparks were produced by discharging a coaxial cable into its characteristic impedance through a 50 Ω coaxial spark chamber, as described previously (Doran and Meyer 1967). The experimental arrangement for producing both streak and shutter photographs is shown in Figure 1. Synchronization was achieved by the sequential firing of trigger spark gaps. Time correlation between the shutter photographs and the discharge current was achieved by applying the voltage pulse, used to close the image converter, to the intensity control grid of the oscilloscope tube, thus dimming the trace at the time of closure.

Streak photographs showing the radius of the discharge as a function of time were obtained by viewing a region of the spark defined by a narrow slit and streaking the image perpendicular to the slit. Axial movements of luminosity were observed by streaking an image of the entire spark perpendicular to its axis.

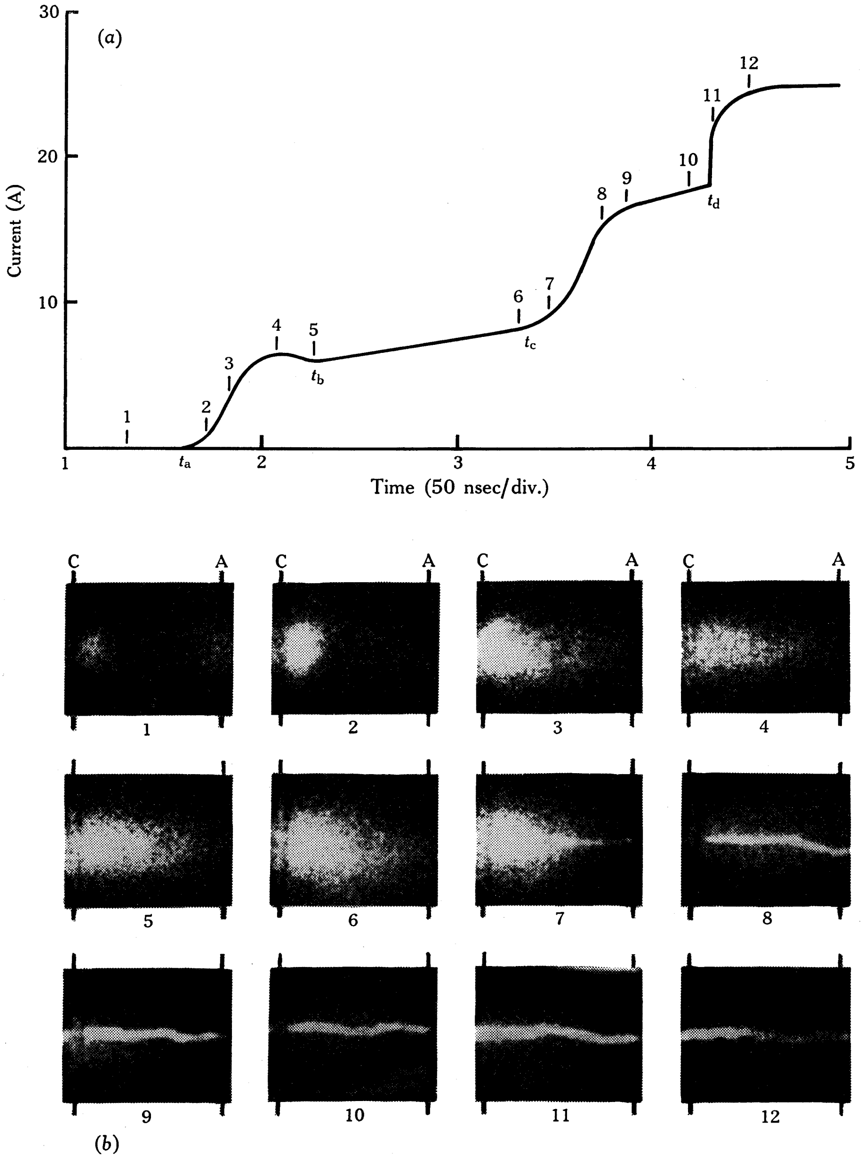

Fig. 2.—Shutter photographs of a discharge in hydrogen at 500 torr ($d = 1 \cdot 8$ mm). Shutter closing times for each frame are indicated on the current oscillogram. C and A mark the positions of the cathode and anode.

A single oscillographic recording of the discharge current enabled a number of electrical discharge parameters to be determined as functions of time.

III. Experimental Results and Discussion

Build-up of currents of the order of amperes through discharges in hydrogen at pressures of between 300 and 700 torr with electrode separations of a few millimetres takes place in three well-defined phases described as the glow, the filamentary glow, and the arc (Doran and Meyer 1967). A typical current oscillogram exhibiting these three phases is shown in Figure 2(*a*). Marked on the oscillogram are the time at which the current is first detected by the oscilloscope t_a, the start of the glow t_b, the start of the filamentary glow t_c, and the start of the arc t_d.

The appearance of the discharge during its development may be deduced from the series of shutter photographs shown in Figure 2(*b*). These show the total integrated light emitted by the discharge up to the time the converter is closed by the gating pulse. The converter closing time for each frame is indicated by the correspondingly numbered mark on the current oscillogram. In order to record satisfactorily the luminosity throughout the development of the spark, the light from the spark was attenuated in the later stages by a reduction in the aperture of the spark chamber lens. As a result, the less intense illumination recorded on the first few frames is absent from the later photographs.

It is shown elsewhere (Meyer 1967) that the light emitted during the early stages of the spark discharge, up to the time t_c, is that of the molecular hydrogen dissociation continuum. Furthermore, the intensity of the maximum of this continuum has been observed to follow closely the variations in discharge current during this period. This suggests that changes in the dissociation continuum intensity may be related to changes in the number of ionizing events. Thus it is possible from a study of the photographs to comment on changes in the rate of ionization and hence on changes in electric field.

(*a*) *Development of a Glow Structure*

The initial development of a discharge at low overvoltage is reasonably well understood and has been treated theoretically by Davies, Evans, and Llewellyn-Jones (1964) and Köhrmann (1964). Köhrmann, using a one-dimensional model and considering only a photon secondary process, calculates the distribution of space charge and the resulting distortion in the applied electric field at various times up to the establishment of the cathode fall. He obtains fields close to the cathode several times greater than the applied electric field, with fields only slightly greater than the applied field within approximately one-third of the electrode gap near the anode. In between these regions the field falls considerably below the originally uniform field.

The shutter photograph shown in frame 1 of Figure 2(*b*), in which the luminosity close to the cathode is separated by a non-luminous region from a less intense glow near the anode, indicates that such a field distribution is in fact established in the early stages of the present discharge.

It is likely that ions produced close to the cathode will eventually move under the influence of this enhanced field and give rise to a more efficient source of electrons from the cathode. As a result of the increased emission, the amount of ionization and positive space charge in front of the cathode increases. This leads to a further concentration of the cathode fall as indicated in frame 5 of Figure 2(*b*) by the growth of a thin intense glow in front of the cathode. This marks the establishment of the quasi-stable diffuse glow.

(*b*) *The Glow* (t_b *to* t_c)

During this period the appearance of the discharge closely resembles that of a high pressure normal glow discharge, exhibiting a uniform positive column, a Faraday dark space, and a negative glow. The cathode glow and cathode dark space are too narrow to be distinguished at these high pressures (cf. frames 5 and 6, Fig. 2(*b*)). In order to investigate the subsequent development of this diffuse glow discharge, the axial distribution of potential and the radial distribution of light intensity were determined as follows.

(i) *Axial Structure*

The procedure normally used to determine the potential distribution of d.c. glow discharges consists of measuring the total voltage across the glow for various electrode separations. In order that variations in the electrode spacing should only affect the length of the positive column and not the cathode region, the current is maintained at a constant value for all separations (Cobine 1941; Gambling and Edels 1954).

In the present investigation, the current at one well-defined time during the transient glow discharge (t_b) was adjusted to the same value at each electrode separation by applying to the spark gap a voltage pulse of the appropriate magnitude. The maximum overvoltage, necessary to attain this current for the smallest electrode separation, amounted to 30%. Whilst the formative time lag and glow duration are both decreased at these higher overvoltages, streak and shutter photographs of discharges produced in the above manner indicate that the diffuse glow itself remains unchanged from that produced at static breakdown.

The voltage distribution for a pressure of 500 torr is shown in Figure 3, curve 3. The open circles correspond to measurements in which the current at each electrode separation was adjusted to 9·5 A. The full circles, lying along the same line, represent additional measurements in which the discharge occurred at applied voltages within 1% of the static breakdown potential (curve 4). In the latter sequence of results the current was not held constant, and in fact varied from 5·9 A for $d = 2{\cdot}5$ mm to 4·1 A for $d = 0{\cdot}4$ mm. These results show that, for the range of current used, the voltage across the discharge during the diffuse glow phase is independent of current.

Gambling and Edels (1954) have suggested that extrapolation of the potential distribution across a high pressure glow discharge to zero electrode separation results in a voltage drop equal to the cathode fall voltage. Present measurements of this "zero length voltage" give a cathode fall of 220 V. This value lies within

16% of the cathode fall voltage, determined using a probe, for low pressure normal glow discharges in hydrogen with cathodes made of copper and zinc, these being the constituents of brass, from which the present cathode is made (Cobine 1941). This agreement with the low pressure discharge suggests that the similarity relation holds for the present situation, i.e. that the product of cathode fall thickness and gas pressure is a constant. For a discharge in molecular hydrogen the value of the constant for both copper and zinc cathodes is $0 \cdot 8$ torr cm (Cobine 1941). Thus for a pressure of 500 torr a cathode fall thickness of $d = 1 \cdot 6 \times 10^{-3}$ cm is obtained. This results in an electric field for the present diffuse discharge, averaged over the cathode dark space, of $1 \cdot 4 \times 10^{5}$ V cm^{-1}.

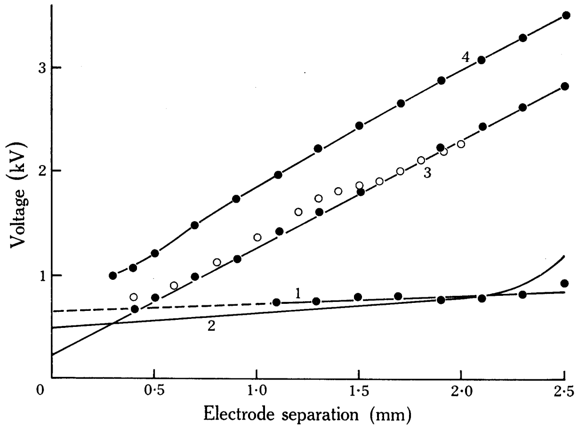

Fig. 3.—Voltage distributions of the discharge at 500 torr:
1 and 2, distribution of the filamentary glow at the time just prior to t_{d},
3, distribution at t_{b},
4, breakdown voltage.

An independent estimate of the cathode fall field has also been made by assuming that the space charge in front of the cathode builds up until it establishes the optimum field for ionization. For this purpose it has been assumed that ion production is predominantly the result of electron–molecule ionizing collision processes, defined in terms of the ionization coefficient α/p. Haydon and Stock (1966) have found that a maximum "effective" value of this coefficient occurs at E/p of the order 300 V cm^{-1} torr^{-1}. For a pressure of 500 torr, appropriate to the present circumstances, this corresponds to a field of $1 \cdot 5 \times 10^{5}$ V cm^{-1}, in good agreement with the above experimentally determined value.

A correlation has been observed, for low pressure glow discharges, between the range of electrons accelerated through the cathode fall voltage and the length of the negative glow (Brewer and Westhaver 1937).

Using the results of Lehmann (1927), the range of electrons of energy 220 eV, in 500 torr of hydrogen is approximately $4 \cdot 0 \times 10^{-3}$ cm. Consequently, if the above relationship applies to the present discharge, the end of the negative glow should occur at a distance from the cathode equal to the sum of the cathode fall thickness and the length of the negative glow; in this case a total distance of $5 \cdot 6 \times 10^{-3}$ cm.

Accurate measurement of this distance on the shutter photographs of Figure 2(*b*) was not possible due to the difficulty in locating the cathode surface on the photographs. It was estimated, however, that the boundary of the negative glow

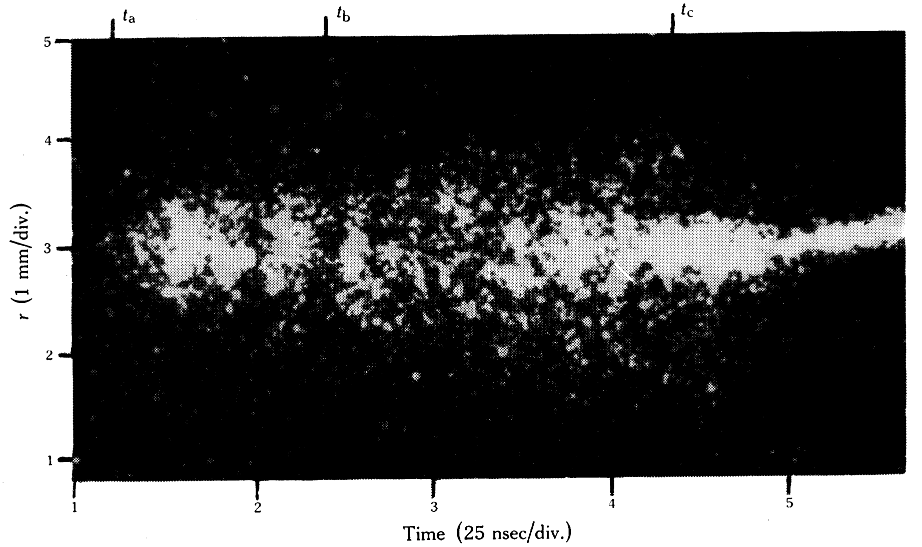

Fig. 4.—Streak photograph of the discharge column (p = 500 torr, d = 2 mm).

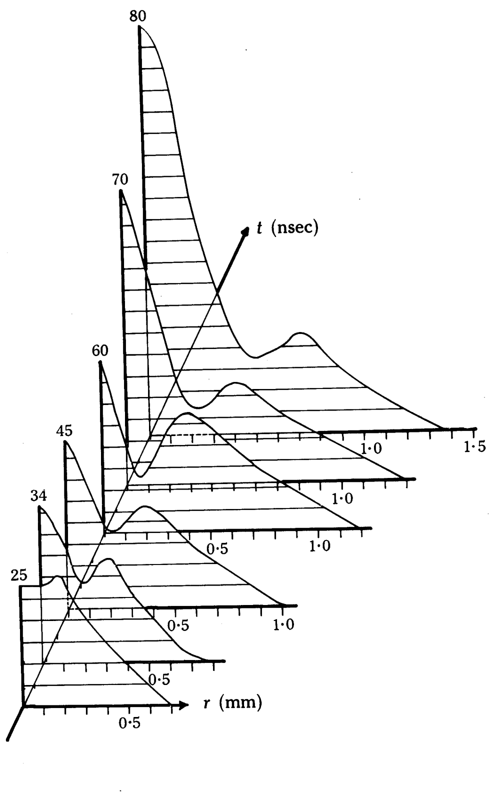

Fig. 5.—Radial distribution of the intensity of the column as a function of time. The values above each curve are the times in nanoseconds after t_a (p = 400 torr, d = 2 mm).

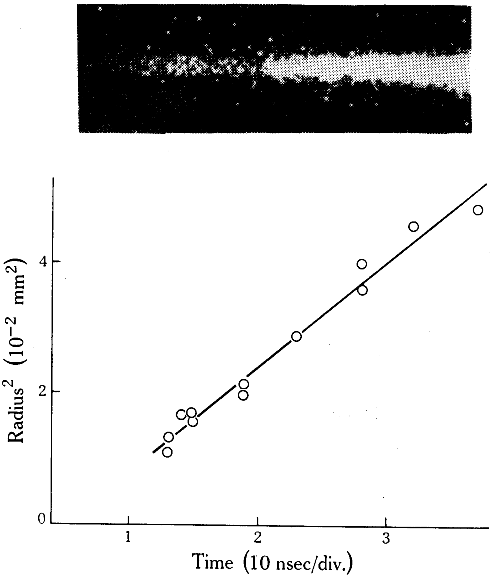

Fig. 6.—Streak photograph of the discharge column at times later than t_c.

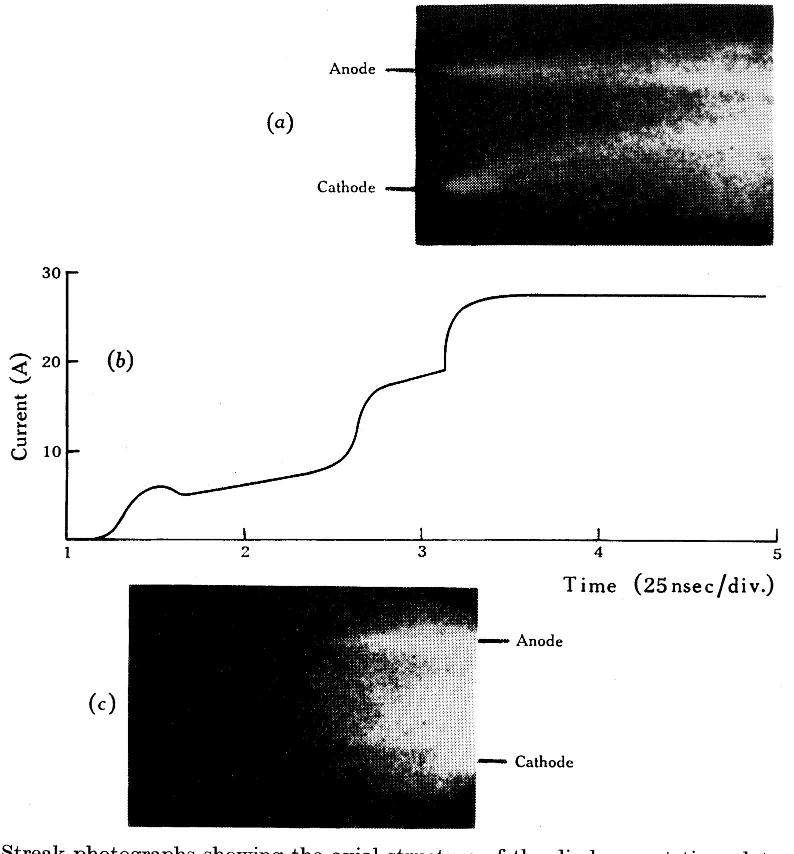

Fig. 7.—Streak photographs showing the axial structure of the discharge at times later than t_c.

extended a distance from the cathode approximately equal to the thickness of the Faraday dark space. At 500 torr this was 5×10^{-3} cm. This agreement further suggests the applicability of established d.c. glow discharge relationships to the present transient discharge.

(ii) *Radial Structure*

A streak photograph showing the radial structure of the discharge column as a function of time is shown in Figure 4. In obtaining this photograph a filter, attenuating the radiation emitted above a wavelength of 4000 Å, was placed in front of the image-converter cathode. Thus, up to the time t_c, the photograph only records the molecular hydrogen dissociation continuum.

At one pressure, 400 torr, microphotometer scans of the photographic negatives were transformed into radial intensity distributions using the Abel integral equation. The radial distribution of intensity at various times is shown in Figure 5 for the position 0·6 mm from the cathode. It may be seen from this diagram that a maximum in the light intensity occurs on the axis of the discharge and is surrounded by a luminous ring that expands at approximately the same rate as the discharge radius, the latter being defined here as the greatest extent over which the luminosity can be detected.

Figure 5 indicates that during the diffuse glow phase two phenomena occur simultaneously. Not only does the positive column expand but also a partial constriction of the column occurs at the same time. Since the radiation recorded by the photographs during the glow is a consequence of electron–molecule collisions, the radial distribution of intensity indicates that a maximum in electron density develops on the axis of the discharge. It is out of this highly conducting central column that the filamentary discharge eventually forms.

In recent years a number of theories have been advanced to explain the phenomenon of constriction of the positive column of a glow discharge. Fowler (1955) has briefly reviewed several of these theories and has himself advanced a collision damping theory of the effect. The applicability of one or other of these theories in the present situation relies on experimental data that have not so far been obtained, namely, radially resolved electron and gas temperatures. Until such information is available a complete description of the partial constriction of the diffuse glow cannot be given.

(c) *The Transition to a Filamentary Glow* (t_c *to* t_d)

Frames 7–10 in Figure 2(*b*) show that following the time t_c a luminous filament appears in the region in front of the anode. The intensity of the luminosity develops subsequently at regions progressively closer to the cathode, appearing at the anode side of the dark space at the time when the current starts to increase linearly once more. Throughout this linear rise, up to the time t_d, the discharge exhibits the same features as during the earlier diffuse glow phase; however, the discharge column is now of a filamentary nature and is much more intense. The transition to a filamentary discharge is also illustrated by the streak photograph of Figure 4. With the increase in current following the time t_c the radius of the glow rapidly constricts whilst the centre of the discharge gains in luminosity, until with the establishment of the second step in the current oscillogram the discharge shows a well-defined filamentary appearance.

A streak photograph of the filamentary glow column, photographed entirely in the light of the atomic radiation, is shown in Figure 6 together with measurements of the radius of the discharge as a function of time. This has been made possible because of the low sensitivity of the image-converter tube in the u.v. region where the most intense part of the molecular radiation is emitted and the rapid increase in intensity in the visible region with the appearance of the Balmer lines (Meyer 1967). This means that attenuation of the light falling onto the photocathode of the image converter has suppressed the molecular radiation that is dominant at times earlier than t_c. The increase in intensity observed in the photograph after approximately 10 nsec corresponds to the establishment of the arc phase described below.

The spectroscopic investigation by Meyer (1967) shows that with the appearance of the filamentary glow, at the time t_c, the radiation emitted by the column consists almost entirely of the line spectrum of atomic hydrogen. This suggests that a substantial increase in dissociation occurs at the time t_c and that the process involved is something other than that of inelastic electron–molecule collisions.

It is probable that the increase in atomic hydrogen is initially due to an increase in the gas temperature (brought about by elastic collisions) which gives rise to some dissociation, a process that becomes important at a gas temperature of about 5000°K. Some evidence for this is obtained from the radial distribution of intensity at times towards the end of the diffuse glow phase which shows a pronounced maximum in electron density developing on the axis of the positive column. As a result, it is to be expected that a similar distribution of gas temperature is established, since elastic electron–molecule collisions are the major cause of gas heating. Due to the increased electrical conductivity along this axial region with the onset of thermal dissociation the entire current flows through this narrow axial column giving rise to the filamentary glow phase.

Accompanying this dissociation is a fast increase in particle density and a rapid increase in pressure along the axis of the discharge. The resulting steep radial pressure gradient eventually leads to the initiation of a cylindrical shock wave shortly after time t_c, which rapidly increases the gas temperature and ensures complete dissociation in a few nanoseconds. The expansion of the shock wave follows an $r \propto t^{\frac{1}{2}}$ law (cf. Fig. 6), which is in agreement with theoretical treatments of cylindrical shock waves (Drabkina 1951; Braginskii 1958). The conditions governing the expansion of the column are set up during the filamentary glow phase. Since these conditions are virtually unchanged by the small additional energy dissipated in the spark channel during the arc, it is not surprising that the expansion of the column continues unaltered with the appearance of the arc channel.

Frame 9 of Figure 2(*b*) shows that during the filamentary glow phase a thin negative glow still covers a wide area of the cathode surface and that the Faraday dark space remains intact. This suggests that the cathode processes at least are similar to those occurring during the diffuse glow, namely, ion impact processes that require a high cathode fall field.

In order to estimate the magnitude of this cathode fall voltage in the filamentary glow phase just prior to t_d the following procedure may be adopted.

Coinciding with the establishment of the arc at the time t_d, an increase in luminosity occurs at the cathode and rapidly appears at progressively greater distances from the cathode. Associated with this is a large increase in conductivity that causes the voltage across the gap to fall to a very small value. It has been assumed that the whole of the voltage across the spark when the bright highly conducting regions are part way across the gap is developed across the remaining less conducting filamentary glow column. This has the same appearance as at the time t_d. By locating the boundary of the extensions of luminosity in the streak photographs of Figure 7, the voltage distribution of the filamentary glow for the time just prior to t_d may then be deduced. This is shown in Figure 3, curve 2, where it may be seen that the majority of the voltage across the discharge at this time appears across the cathode fall region.

An alternative estimate of the potential distribution was made from measurements of the voltage at the time t_d as a function of gap separation. The results are shown in Figure 3, curve 1, which, over the range of electrode separations for which the method was feasible, agrees reasonably well with the above determination.

The cathode fall voltage for the filamentary glow, as given by the intercept on the voltage axis, exceeds that of the diffuse glow by a factor of approximately two. Lack of further information prevents an explanation of this phenomenon at this stage; however, the large increase in current density that occurs at the same time in the column suggests that the discharge may have undergone a transition to an abnormal glow on constriction of the column.

(*d*) *The Arc*

The last two frames of the shutter photographs in Figure 2(*b*) show that at the time t_d the luminosity extends right up to the cathode surface thus finally bridging the dark space in front of the cathode. With the rapid rise of current, the filamentary discharge increases in intensity and continues to expand radially.

Streak photographs having the time axis perpendicular to the channel axis are shown in Figures 7(*a*) and 7(*c*). The photographs have been positioned so as to share a common time axis with the current oscillogram (Fig. 7(*b*)). Figure 7(*a*) shows that at the time t_d an intense luminosity appears in front of the cathode which subsequently extends towards the anode with a velocity of 4×10^6 cm sec^{-1}. A similar luminosity appears at the anode at the time t_c and extends towards the cathode with a velocity of approximately 10^6 cm sec^{-1}. Some 40 nsec after t_d the two extensions of luminosity meet at a position close to the anode. One of these, the extension of luminosity originating at the cathode, is observed in frame 12 of Figure 2(*b*) to have reached part way across the gap, with the remainder of the gap having the appearance of the earlier filamentary glow phase.

Figure 7(*c*) shows the start of both the luminosity originating at the anode at time t_c and that originating near the cathode at time t_d. This photograph also shows the dark space that remains intact up to the time of establishment of the arc.

At the time t_d a significant change in cathode mechanism occurs enabling the entire discharge current to proceed from a very small area of the cathode surface. The rapid increase in current that occurs (several amperes in less than 1 nsec) suggests that the current may be provided by field emission.

IV. Conclusions

This investigation has provided evidence in support of the assumption that the ionized channel of a spark discharge at low overvoltage develops out of the superposition of many electron avalanches which, through the build-up and redistribution of positive space charge, give rise first to a diffuse glow discharge. This glow discharge, in which electron–molecule collisions predominate, exhibits a cathode fall region and a positive column across which a considerable potential gradient exists.

Measurements of the cathode fall voltage and of the position of the Faraday dark space have shown that a close similarity exists between this transient glow and the d.c. glow discharge. This agreement suggests that many of the features of the transient discharge, at present difficult to study, may be investigated further by means of experiments carried out on the d.c. discharge.

The radial distribution of intensity of the light emitted during the diffuse glow indicates that, even while the radius of the discharge expands, a progressively greater proportion of the current passes through a narrow column located on the axis of the discharge. It has been suggested that this localized region of high electron density causes the gas temperature to rise by electron–molecule collisions until thermal dissociation occurs. The resulting build-up in atomic hydrogen is restricted to this narrow axial region, which, due to its higher electrical conductivity, soon carries the entire discharge current.

The column of the discharge at this time appears filamentary and consequently more intense than the earlier diffuse phase. The cathode region, on the other hand, still exhibits a Faraday dark space and a negative glow covering a wide area of the cathode surface.

After maintaining a high cathode fall voltage for a short time a significant change in cathode mechanism occurs which gives rise to a rapid burst of ionization at the cathode surface. This increase in ionization develops progressively towards the anode along the partially ionized filamentary path causing the total collapse of voltage across the spark.

Whilst some progress has been made in this investigation in understanding the diffuse glow to filamentary glow transition, considerably more work needs to be done to understand the nature of the later transition to the arc. Since the present investigation has been able to establish the point in time at which the cathode processes become dominant and to correlate this with oscillographic and photographic observations, it should be possible to carry out a more controlled study of the effect of surface irregularities and cathode material on the glow to arc transition.

V. Acknowledgments

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VI. References

Braginskii, S. I. (1958).—*Soviet Phys. JETP* **34**, 1068.

Brewer, A. K., and Westhaver, J. W. (1937).—*J. appl. Phys.* **8**, 779.

Cobine, J. D. (1941).—"Gaseous Conductors." (McGraw-Hill: New York.)

Davies, A. J., Evans, C. J., and Llewellyn-Jones, F. (1964).—*Proc. R. Soc.* A **281**, 164.

Doran, A. A., and Meyer, J. (1967).—*Brit. J. appl. Phys.* **18**, 793.

Drabkina, S. I. (1951).—*Soviet Phys. JETP* **21**, 473.

Fowler, R. G. (1955).—*Proc. phys. Soc.* **68**, 130.

Gambling, W. A., and Edels, H. (1954).—*Brit. J. appl. Phys.* **5**, 36.

Haydon, S. C., and Stock, H. M. P. (1966).—*Aust. J. Phys.* **19**, 795.

Köhrmann, W. (1964).—*Z. Naturf.* **19a**, 926.

Lehmann, J. F. (1927).—*Proc. R. Soc.* **115**, 624.

Meyer, J. (1967).—Physics Department Internal Rep., University of New England.

Raether, H. (1964).—"Electron Avalanches and Breakdown in Gases." (Butterworths: London.)