Transient Breakdown Studies in Hydrogen at Low Values of E/p*

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Formative time lag measurements of uniform field breakdown have been carried out in hydrogen for products of pressure p and electrode separation d ranging from 100 to 1300 cm×mm Hg. This pd range corresponds to a region of electric field strength E divided by p at the breakdown threshold of between 21 and 32 v (cm mm Hg)$^{-1}$. The formative time lags decrease from about 50 μsec at several hundredths of a percent overvoltage to fractions of a microsecond for overvoltages greater than 5%. The results indicate that the secondary mechanism active is photoelectric emission from the cathode.

INTRODUCTION

FORMATIVE time lags of uniform field breakdown at voltages close to the breakdown threshold have been measured previously for pressures p between about 100 and 700 mm Hg and for electrode separations d up to a few centimeters[1] for air,[2] nitrogen,[3] and argon.[4] Furthermore, the current during the formative time lag has been measured for $p\sim 667$ and $d=1$ in air[5] and for $50<p<600$ and for $0.5<d<1.5$ in argon.[6] The above work indicates the existence of photoelectric emission from the cathode as the secondary process active during the current buildup preceding breakdown. In the case of air and nitrogen, the radiation incident on the cathode is transported through the gas with the velocity of light[7]; in argon the radiation is delayed, probably because of the imprisonment of resonance radiation.[4,6,8]

In any attempt to analyze formative time lag data, it is necessary to have values available of α/p, γ, v_-, and v_+ (the first Townsend coefficient divided by p, the second Townsend coefficient, the electron drift velocity, and the positive-ion drift velocity, respectively) as functions of E/p, the ratio of electric field strength to p. The quantity α/p is the most critical parameter in the analysis because of its rapid variation with E/p. At the present time, hydrogen is the only gas for which there is good agreement about the values of α/p over a considerable range of E/p. Thus a more precise analysis of any experimentally obtained time lag data would be possible for hydrogen than for any other gas. Since there were no available formative time lag measurements in hydrogen for the same pd region for which formative time lags were studied in the gases mentioned above, the present work was undertaken. Actually, extensive formative time lag measurements were carried out in hydrogen for $100<pd<1200$ (with a brass cathode) in this laboratory some time ago.[9,10] This pd range[11,12] corresponds to a range of E/p at the breakdown threshold of about 21 to 32 v (cm mm Hg)$^{-1}$. The results, however, were not published in full owing to uncertainty then existing in the values of α/p. The present paper reports time lag measurements recently carried out in hydrogen with a nickel cathode for values of E/p at the breakdown threshold between 21 and 32.

APPARATUS AND EXPERIMENTAL PROCEDURE

The apparatus has been described previously.[3] It was possible to stabilize the cathode by running a glow discharge in hydrogen in a manner also described previously.[13] Values of I_0, the externally produced current at the cathode, were calculated from prebreakdown current measurements using the values of α/p given by Rose.[14] Such currents were measured at voltages sufficiently low such that the condition $\gamma[\exp(\alpha d)-1]\ll 1$ obtained. The value of I_0 was generally about 10^{-11} amp. Linde tank hydrogen which had been passed over liquid air was used. The values of α/p for hydrogen obtained for $15<E/p<24$ in the present chamber[13] with gas purity comparable to that of the present experiment agree with those of Rose[14,15]

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[1] Unless otherwise mentioned, all statements refer to these ranges of p and d. Units of p and d are omitted throughout but are to be understood as being mm of Hg at 0°C and cm, respectively.

[2] L. H. Fisher and B. Bederson, Phys. Rev. **81**, 109 (1951).

[3] G. A. Kachickas and L. H. Fisher, Phys. Rev. **88**, 878 (1952).

[4] G. A. Kachickas and L. H. Fisher, Phys. Rev. **91**, 775 (1953).

[5] H. Bandel, Phys. Rev. **95**, 1117 (1954).

[6] M. Menes, Phys. Rev. **116**, 481 (1959).

[7] A subsequent analysis of the formative time lag data in air of reference 2 at one particular set of values of p and d ($p\sim 730$, $d=1$) has been carried out by J. Dutton, S. C. Haydon, F. Llewellyn Jones, and P. M. Davidson, Brit. J. Appl. Phys. **4**, 170 (1953). These authors agree that the secondary emission for the above case is primarily due to photoelectric action at the cathode, but believe that a small fraction of the secondary emission of electrons is also due to positive-ion bombardment of the cathode.

[8] D. E. Golden and L. H. Fisher, Phys. Rev. **123**, 1079 (1961).

[9] I. Lessin and L. H. Fisher, Phys. Rev. **93**, 649 (1954).

[10] I. Lessin, Ph.D. thesis, New York University, 1953 (unpublished).

[11] Units of E are given in v/cm throughout.

[12] Formative time lags in hydrogen for $pd<50$ have been measured by C. G. Morgan, Phys. Rev. **104**, 566 (1956) for $50<E/p<400$ and by F. Llewellyn Jones and E. Jones, Proc. Phys. Soc. (London) **75**, 762 (1960) for $50<E/p<250$. The formative time lags in hydrogen in this low-pd region were explained by assuming that secondary emission at the cathode is partly due to positive-ion bombardment and partly due to photoemission (see reference 7). Although these authors agree in assigning a role to both photoelectric and positive-ion action as secondary mechanisms in hydrogen for the ranges of E/p which they studied, they differ radically in their estimate of the relative importance of the two mechanisms.

[13] D. J. DeBitetto and L. H. Fisher, Phys. Rev. **104**, 1213 (1956).

[14] D. J. Rose, Phys. Rev. **104**, 273 (1956).

[15] D. J. Rose, D. J. DeBitetto, and L. H. Fisher, Nature **177**, 945 (1956).

for this same range of E/p obtained with very pure hydrogen. Thus it may be assumed that impurities play little or no role in the present study.

A pulsed sparking potential V_s (measured with $I_0 \sim 10^{-11}$ amp), was used to define the threshold voltage for breakdown. The value of V_s at a given set of values of p and d was found to be constant with repeated trials (carried out within about an hour) to within several volts. A 2000-v pulse was used both to determine V_s and to determine the formative time lags.

For every overvoltage studied at each set of values of p and d, ten measurements of the formative time lag were made. Each set of ten measurements usually showed a maximum deviation of about 30% from the average, and the average value of a set of ten such measurements was taken to be the time lag τ. Values of τ were obtained at four values of d (0.5, 1.0, 1.5, and 2.0) and at four values of p (190, 282, 463, and 654). Overvoltages were varied from several hundredths of a percent to about 10%.

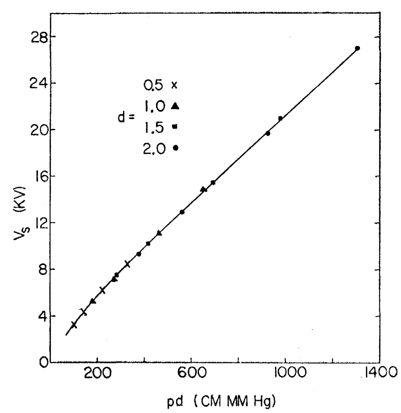

FIG. 1. Pulsed breakdown potential V_s vs pd obtained at the values of d indicated.

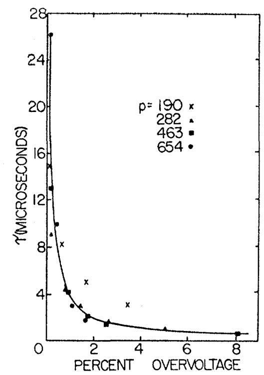

FIG. 2. Measured values of formative time lag τ vs percent overvoltage at $d=0.5$ at values of p indicated.

EXPERIMENTAL RESULTS

Figure 1 represents the observed pulsed breakdown potential V_s vs pd in hydrogen for a nickel cathode with $I_0 \sim 10^{-11}$ amp. These measurements are in good agreement (to within about 5%) with the breakdown measurements in hydrogen of Schöfer[16] (carried out for $pd<200$), of Ehrenkranz[17] (carried out for $pd<300$), of Fucks and Kettel[18] (carried out for $pd<400$), and of Lessin[10] (carried out for $100<pd<1200$). The cathodes used in the above work were as follows: Ehrenkranz and Fucks and Kettel, platinum; Schöfer, nickel; and Lessin, brass.

Measured values of τ vs percent overvoltage are given in Figs. 2–5 for $d=0.5$, 1.0, 1.5, and 2.0, respectively, at the four pressures studied. (These results are very close to those obtained previously in this laboratory with a brass cathode.[9,10]) It should be noted that the time lags in hydrogen when plotted against percent overvoltage are independent of pressure as previously observed in air and nitrogen[2,3] (except for $p=190$, $d=0.5$ as seen in Fig. 2). Observed values of τ are plotted vs percent overvoltage for $p=654$ in Fig. 6 at the four values of d studied. At a given percent overvoltage, τ increases with increasing d; this is typical of the results obtained at the three other values of p studied. The observed variation of τ with d in hydrogen is also similar to that previously observed in air and nitrogen.[2,3]

DISCUSSION

The nature of the secondary processes active during the formative time lag may be determined using a very simple approximate calculation previously given.[4] The results for the case where all secondary action is photoelectric in nature will be discussed first. Suppose a voltage V is applied to an irradiated gap at time zero, and let the values of the first Townsend coefficient and of the electron velocity at the voltage applied be α and v_-, respectively. All photons are assumed to be created very near the anode; it is further assumed that the time

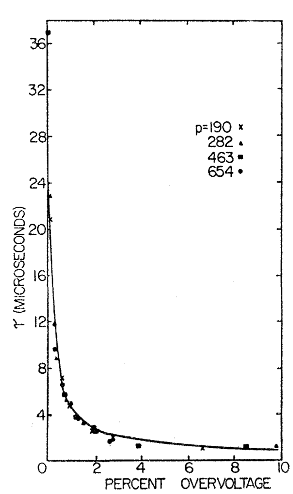

FIG. 3. Measured values of formative time lag τ vs percent overvoltage at $d=1.0$ at values of p indicated.

[16] R. Schöfer, Z. Physik **110**, 21 (1938).
[17] F. Ehrenkranz, Phys. Rev. **55**, 219 (1939).
[18] W. Fucks and F. Kettel, Z. Physik **116**, 667 (1940).

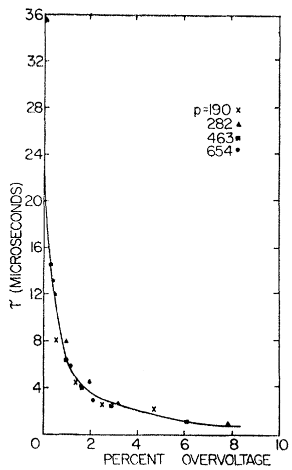

FIG. 4. Measured values of formative time lag τ vs percent overvoltage at $d=1.5$ at values of p indicated.

for a photon to cross the gap is negligible. It is assumed that breakdown occurs (if $V>V_s$) when the number of electrons liberated from the cathode as the result of a single electron being emitted at an earlier time reaches a value N.[19] Then breakdown will occur after n_- electron transits if the following condition is satisfied:

$$[\gamma \exp(\alpha d)]^{n_-}=N, \tag{1}$$

where $\exp(\alpha d)$ has been assumed to be much greater than unity. The breakdown threshold is determined by

$$\gamma \exp(\alpha_s d)=1, \tag{2}$$

where α_s is the value of the first Townsend coefficient at threshold, where γ is assumed to be independent of overvoltage, and where $\exp(\alpha_s d)$ has also been assumed to be much greater than unity. Under these assumptions, it is possible to eliminate γ from Eqs. (1) and (2), and one obtains the relation

$$\exp[n_- d(\alpha-\alpha_s)]=N. \tag{3}$$

Since $n_- d=v_-\tau$, where τ is the formative time lag, Eq.

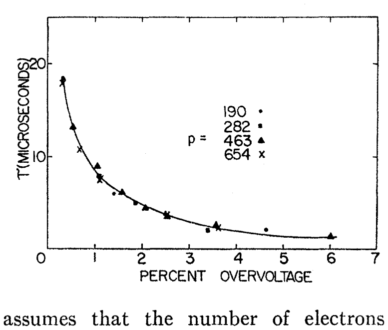

FIG. 5. Measured values of formative time lag τ vs percent overvoltage at $d=2.0$ at values of p indicated.

[19] This formulation assumes that the number of electrons emitted from the cathode is uninfluenced by space charge and that when a critical number of electrons is released from the cathode breakdown occurs in a negligible time. Although it is believed that this gives a fairly accurate value for the breakdown time, space charge effects do become appreciable when the current exceeds some tens of microamperes as shown by Menes (See reference 6).

(3) may be written

$$\tau=(\ln N)/[v_-(\alpha-\alpha_s)]. \tag{4}$$

If, however, secondary emission occurs only by positive ion bombardment of the cathode rather than only by photoemission, Eq. (4) will give a corresponding expression for τ providing v_- is replaced by v_+, the positive-ion velocity. Thus for a chosen value of $\ln N$ (a reasonable value would seem to be about 15 or 20) one may predict τ as a function of percent overvoltage on the basis of either one of the above mechanisms if α/p, v_-, and v_+ are known functions of E/p. Values of $\ln N$ were calculated with Eq. (4) for hydrogen from the observed values of τ using measured values[14] of α/p and values of v_- extrapolated from measurements made at values of E/p lower than those studied in the present experiment.[20] The average value found for $\ln N$ for all values of p, d, and percent overvoltage studied is 17.8 with an average deviation of 8.0. If the measurements

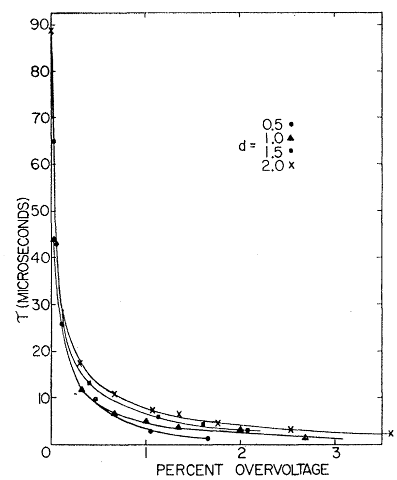

FIG. 6. Measured values of formative time lag τ vs percent overvoltage at $p=654$ at values of d indicated.

for $E/p=32$ at breakdown are excluded (these are the measurements for $d=0.5$, $p=190$ shown in Fig. 2), one obtains an average value of $\ln N$ of 14.0 with an average deviation of 5.0. The agreement is even much better than that obtained with air and nitrogen, where the fit was considered excellent.[3] If one excludes the data at the lowest overvoltage studied at each value of p and d [where the percentage error in $(\alpha-\alpha_s)$ is very large] one obtains an average value of $\ln N$ of 15.3 with an average deviation of only 3.4. Furthermore, the magnitude of $\ln N$ obtained indicates photoelectric emission as the secondary process liberating electrons from the cathode. The assumption of only a positive ion secondary mechanism would give an unsatisfactorily small value for $\ln N$, and hence this secondary mechanism may be assumed to play only a very small role during the buildup in comparison to that played by photoelectric action at the cathode.

[20] N. E. Bradbury and R. A. Nielsen, Phys. Rev. 49, 388 (1936).