High-Voltage Glow Discharges in D_2 Gas. III. Starting Potential Theory*

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A theoretical treatment of the left branch of the Paschen curve for parallel plate discharges in D_2 gas is presented for potentials ranging from 5 to 120 kv. The effect of electrons backscattered from the anode is considered and found to be significant. The Paschen curve is found to be extremely sensitive to the secondary emission coefficient at low energies. It is demonstrated that even the sign of the slope of the Paschen curve depends on the energy dependence of the secondary emission coefficient.

INTRODUCTION

In part I[1] of this series the results of experiments with high-voltage (40–80 kv) glow discharges were presented. In part II[2] a mathematical description of the cathode fall region of such discharges in terms of elementary collision processes was given which showed excellent agreement with the experimental results. Using a similar model and many of the approximations that were presented in part II, starting potential curves were calculated; the results of these calculations are presented in this paper.

THEORETICAL CONSIDERATIONS

The same types of collisions and the same values of the collision cross sections were used as were discussed and used in the calculations of part II. The secondary emission coefficient was altered somewhat from that assumed in part II; this will be discussed later in this paper. The only other changes in the mathematical model were as follows:

1. Instead of using Poisson's equation to determine the electric field a constant field was assumed since the space charge density is negligible under the small current (starting) conditions assumed.

2. The source of ions flowing from the plasma was omitted (since there is no plasma under the conditions considered here); the whole volume between anode and cathode was the region of interest.

3. The ionizing effect of electrons backscattered from the anode was taken partially into account. That is, ionization due to the first parabolic orbits of backscattered secondary electrons was rigorously accounted for. Electron orbits resulting from second or succeeding backscattering of the same electron were ignored. Ionization due to electrons released in the gas from ionizing collisions was ignored (as it was in part II); the effect of these electrons after backscattering from the anode was also ignored. The secondary electrons were assumed to impinge normally on the anode. The backscatter coefficient as a function of energy was assumed to follow the curve given by Kulenkampff and Ruttiger[3] for Ni at 137° backscatter angle. The angular distribution was assumed to follow the relationship $dN/d\Omega \propto \cos\theta$.

4. The multiplication, M, was defined as follows. For a given applied potential and tube length a secondary emission current density was assumed. The calculation then proceeded as in part II and a calculated value of secondary emission current density obtained. Then M was defined as: $M=$ (calculated secondary emission current density)/(assumed secondary emission current density). Points on the starting potential curve have $M=1$.

In the discussion which follows, d is the anode-cathode spacing; it will, however, always be referred to in the "reduced" form, pd, where p is the pressure.

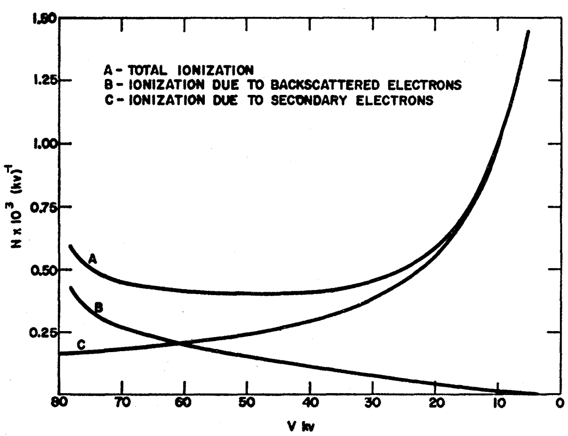

FIG. 1. Number of D_2^+ ions produced in the D_2 gas per secondary electron per kv increment of tube length (N) vs potential relative to the cathode (V). The reduced anode-cathode spacing (pd) is 0.65 mm Hg-cm. The applied potential is 80 kv.

RESULTS

The distribution of D_2^+ ions as formed in the D_2 gas by secondaries and by backscattered secondaries is illustrated in Fig. 1. Although the backscattered electrons account for only $\frac{1}{6}$ to $\frac{1}{5}$ of the total ionization, they make a very significant contribution to the multiplication. For the case illustrated in Fig. 1 the following values of M were found: M(backscatter included) $=1.38$ and M(backscatter omitted) $=0.68$. The importance of the ions produced by backscattered

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[1] G. W. McClure, Phys. Rev. **124**, 969 (1961).

[2] G. W. McClure and K. D. Granzow, Phys. Rev. **125**, 3 (1962).

[3] H. Kulenkampff and K. Ruttiger, Z. Physik **152**, 249 (1958).

electrons arises from the fact that a high concentration of them is produced near the anode; thus most of them move a large fraction of the distance from anode to cathode ionizing other gas molecules on the way. The ions produced directly by secondary electrons are concentrated near the cathode; most of them move only a short distance before striking the cathode and thus, on the average, ionize fewer gas molecules per ion than do the ions produced by backscattered electrons.

In the calculations of part II the experimental secondary emission coefficient was used which was presented in part I with the low energy (below 15 kev for D_2^+, 7.5 kev for D and D^+) portion of the curve extrapolated linearly to zero at zero energy. In calculating starting potential curves more consideration must be given to the low energy extrapolation of γ. This is because in the small-current case ionization by

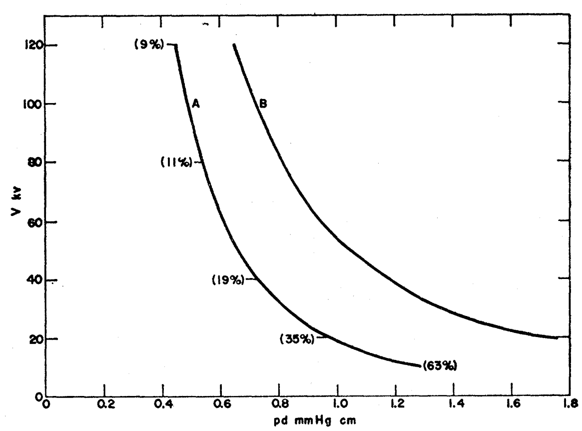

FIG. 2. Theoretical starting potential (V) vs reduced anode-cathode spacing (pd) with the effect of backscatter included (curve A), and with it omitted (curve B). The low energy extrapolation of γ is 1.0 power of energy. The numbers in parentheses indicate the number of electrons released in the gas due to ionizing collisions expressed as a percentage of the number of secondary electrons.

secondary emission electrons (and subsequent backscattered electrons) is the only mechanism supplying ions to the cascade and because there is a high concentration of low energy particles impinging on the cathode.[4] Therefore, calculated starting potential curves are given for several different extrapolations of the secondary emission curve. For each extrapolation a starting potential curve is presented with the effect of backscatter included and one is presented with the effect of backscatter omitted for comparison.

[4] The ion spectra incident on the cathode in the small current case are qualitatively the same as those presented in part II (i.e., they contain a high concentration of low energy D atoms). In the high current case of part II, ions supplied to the cathode fall region from the plasma were more important than those supplied by the ionizing effect of secondary electrons. Thus, the low energy extrapolation of the secondary emission coefficient was much less important in that theory than in the small current theory presented here (in which there is no supply of ions from a plasma).

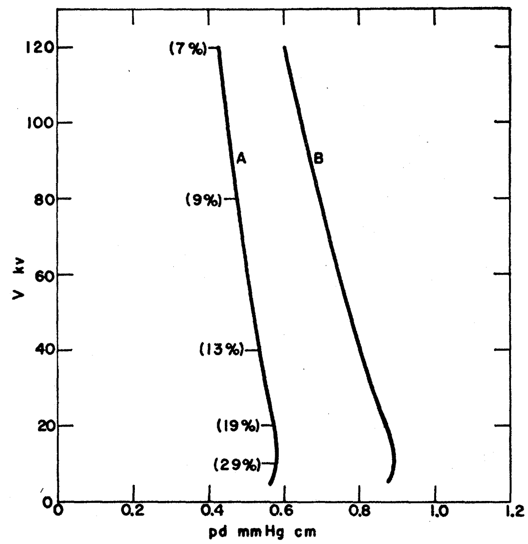

FIG. 3. Theoretical starting potential (V) vs reduced anode-cathode spacing (pd) with the effect of backscatter included (curve A) and with it omitted (curve B). The low energy extrapolation of γ is 0.7 power of energy. The numbers in parentheses indicate the number of electrons released in the gas due to ionizing collisions expressed as a percentage of the number of secondary electrons.

Figures 2, 3, and 4 show calculated starting potential curves for γ extrapolated according to 1.0-, 0.7-, and 0.5-power laws respectively. The 0.7- and 0.5-power-law extrapolations were not only chosen because they

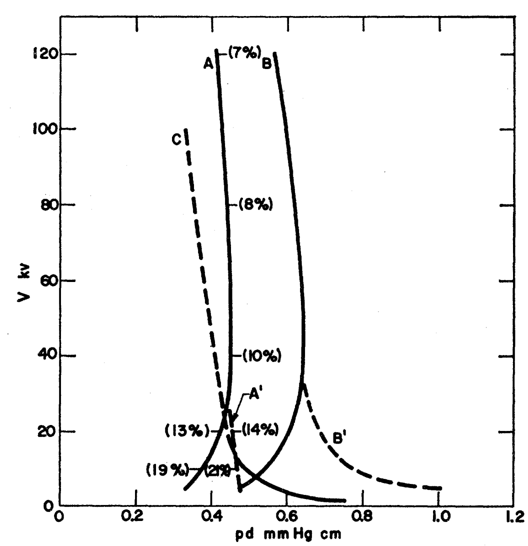

FIG. 4. Theoretical starting potential (V) vs reduced anode-cathode spacing (pd) with the effect of backscatter included (curves A and A') and with it omitted (curves B and B'). The low energy extrapolation of γ for curves A and B is 0.5 power of energy. For curves A' and B', γ is the same as for A and B for $E \geq 0.6$ kev; below 0.6 kev γ falls sharply with energy as described in the text. The numbers in parentheses indicate the number of electrons released in the gas due to ionizing collisions expressed as a percentage of the number of secondary electrons. Curve C is an experimental starting potential curve reported by McClure[6] (solid portion) extrapolated by a power law (dashed portion).

yielded more realistic starting potential curves than the linear extrapolation, but a number of reported secondary emission coefficients[5] for hydrogen were plotted on log-log paper and, in general, they can be approximated by a power law between 0.54 and 1.0 in the energy range of interest. Thus, on the basis of available information, these extrapolations are reasonable. Curve C in Fig. 4 is an experimental starting potential curve reported by McClure[6] (solid portion) extrapolated by a power law (dashed portion). The dashed curves A' and B' are given simply to illustrate the extreme sensitivity of the shape of the starting potential curve to changes in the secondary emission coefficients at low energies. For these curves $\gamma(E)$ was the same as for curves A and B (0.5-power-law extrapolation) for $E \geq 0.6$ kev; for $E < 0.6$ kev $\gamma(E)$ was assumed to vary linearly from $E=0$, $\gamma=0$ to $E=0.4$ kev, $\gamma=0.4$ and linearly from this point to $E=0.6$ kev, $\gamma=1.24$ (a point on the 0.5-power-law extrapolation). This modification represents a sharp decrease (with respect to the 0.5-power law) in γ below 0.6 kev. The sensitivity of the starting potential curve to changes in γ has been pointed out by H. Neu in a simpler theory.[7]

In the starting potential theory reported here as well as the theory of part II, ionization by electrons released in the gas by ionizing collisions was ignored. This approximation resulted in negligible error in the results of part II. However, in some of the starting potential calculations given here these "second generation" electrons achieve some significance especially for low applied potentials and large interelectrode spacings. The current density of electrons released in the gas expressed as a percentage of the secondary electron current density is shown numerically at points along the starting potential curves. Since these electrons move only part of the distance between electrodes they cannot on the average produce as many ions per electron as secondary electrons do; thus, their significance is somewhat less than the percentages given might indicate. However, if they were included, the starting potential curves would be shifted slightly to the left. Inclusion of the effect of these electrons would greatly increase the difficulty of the computations.

CONCLUSION

Backscatter is an important effect in the starting mechanism of the discharge since (1) its inclusion significantly shifts the starting potential curve and (2) for a constant applied potential and electrode spacing it significantly affects the multiplication. Due to the extreme sensitivity of the starting potential curve to the behavior of γ at low energies, a better correlation between theory and experiment cannot be expected until γ (especially for neutrals) is known more accurately for low energies. The theory given here suggests that γ behaves as about a 0.5- to 0.7-power law of energy between 1 and 15 kev; otherwise the theoretical starting potential curve does not even come near meeting the experimental curve. One might further speculate that γ (at least for the important D atoms) decreases sharply with decreasing energy somewhere below 1 kev such as to give the Paschen curve negative slope in the low applied-potential region.[8]

[5] H. C. Bourne, R. W. Cloud, and J. G. Trump, J. Appl. Phys. **26**, 596 (1955); M. Healea and E. L. Chaffee, Phys. Rev. **49**, 925 (1936); M. Healea, Phys. Rev. **55**, 984 (1939); V. G. Telkovskii, Soviet Phys.—Doklady **1**, 334 (1957); S. N. Ghosh and W. F. Sheridan, J. Chem. Phys. **26**, 480 (1957).

[6] G. W. McClure, J. Electronics and Control **7**, 439 (1959).

[7] H. Neu, Z. Physik **155**, 77 (1959).

[8] The low-energy drop-off of γ for neutrals is also suggested by secondary emission curves given for He and A atoms by A. Rostagni [Nuovo cimento **11**, 99 (1934)]. Rostagni's data (and reference to it) were taken from H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford University Press, New York, 1956), Chap. 8, p. 490.