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Pressure-Dependent Breakdown Potentials in Penning Mixtures

LORNE M. CHANIN AND G. D. RORK
Honeywell Research Center, Hopkins, Minnesota
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Measurements have been made of the primary and secondary electron ionization coefficients in neon–hydrogen, helium–hydrogen, and neon–argon mixtures using the Townsend technique. In these experiments, measurements have been conducted over a considerable range of pressures at the E/p_0 value corresponding to the maximum of the Penning effect and for the optimum concentrations. Examination of the prebreakdown current growth indicated at fixed E/p_0 a pressure-dependent breakdown potential. Measurements of the primary coefficient as a function of pressure showed no significant pressure variation. Measurements of the secondary ionization coefficient, however, indicated that γ decreased with increasing pressure consistent with the observed breakdown potential variation.

I. INTRODUCTION

IN 1957 Frouws[1] reported a pressure dependence of the Penning effect in neon–argon mixtures. In a series of measurements of the breakdown potential in plane parallel geometry for various concentrations of argon in neon, he observed that at constant p_0x the breakdown potential increased as the total gas pressure was increased. No detailed explanation for this effect was given; however, it was suggested that three-body destruction of metastable states could conceivably account for the measured effect, since a decrease in metastable density would result in less ionization due to the Penning effect. We have recently measured the primary electron ionization coefficient in helium–hydrogen, neon–hydrogen, and neon–argon mixtures, as a function of the minor constituent concentration and total gas pressure.[2] In these measurements at fixed E/p_0 an apparent variation of the breakdown potential with total pressure was observed. The present paper describes the results of a study directed towards an attempt to account for the observed variation.

The technique used in the present studies involved the standard Townsend[3] method of prebreakdown current growth analysis. The growth of prebreakdown currents in uniform fields as the result of ionization by electron impact and secondary electron production is given by

$$\frac{I(V)}{I(0)}=\frac{\exp\eta(V-V_0)}{1-\gamma\{\exp[\eta(V-V_0)]-1\}} \qquad (1)$$

for $V\geq V_0$. Here η is the ionization efficiency function which is related to the primary coefficient α by $\eta=\alpha/E$ (electric field E), γ is the generalized secondary coefficient, $I(0)$ is a small initial photoelectric current (externally generated), V is the potential applied between the electrodes, and V_0 is related to the minimum potential the electron swarm must traverse in order to attain equilibrium with the applied E/p_0 ($p_0=273\,p/T$). The derivation of Eq. (1) involves several assumptions. The applied field is assumed to be uniform. The electrons are assumed to be in equilibrium with the field for $V\geq V_0$. Space-charge effects are assumed to be negligible. Moreover, electron losses by diffusion and attachment processes are neglected, and finally η and γ are assumed constant independent of V. Townsend showed that by measuring three currents I_1, I_2, and I_3 corresponding to potentials V_1, V_2, and V_3 such that $V_1<V_2<V_3$, η could be evaluated without any information necessary concerning $I(0)$, V_0, or γ. This method has been used by Kruithof and Penning[4] for the case of $V_2-V_1=V_3-V_2=\Delta V$, for which they have shown that η can be evaluated from

$$\exp\eta\Delta V=I_3(I_2-I_1)/I_1(I_3-I_2). \qquad (2)$$

Davies and Milne[5] have shown that γ may be evaluated from the expression

$$\gamma=\frac{I_3-I_2\exp[\eta(V_3-V_2)]}{I_3I_2\{\exp[\eta(V_3-V_2)]-1\}}\cdot I(0). \qquad (3)$$

In the present work η and γ were evaluated using Eqs. (2) and (3). The values of $I(0)$ were inferred[6] from the $\ln I(V)$ vs V plots by extrapolation to $V=0$.

The breakdown potentials (V_B) were estimated from the $\ln I$ vs V curves by extrapolation of the curved portions to their asymptotic values. While this method of measuring the breakdown potentials assumes the validity of the Townsend mechanisms in describing breakdown and is probably not more accurate than $\pm 5\%$, it was believed essential to measure η, γ, and V_B in the same apparatus and to restrict current values to less than 10^{-9} A/cm^2 in order that the values of γ would not be seriously altered as the result of cathode bombardment. Moreover, as will be subsequently evi-

[1] S. M. Frouws, *Proceedings of the Third International Conference on Ionization Phenomena in Gases, Venice, 1957* (North-Holland Publishing Company, Amsterdam, 1958), p. 341.
[2] L. M. Chanin and G. D. Rork, Phys. Rev. **135**, A71 (1964).
[3] An excellent summary of work in this field is given in L. B. Loeb, *Basic Processes of Gaseous Electronics* (University of California Press, Berkeley, 1955), Chap. 8.
[4] A. A. Kruithof and F. M. Penning, Physica **3**, 515 (1936).
[5] D. E. Davies and J. G. C. Milne, Brit. J. Appl. Phys. **10**, 301 (1959).
[6] Values of $I(0)$ were also calculated using a formula given by Loeb (Ref. 3, p. 660). Values of $I(0)$ obtained using both methods were found to be in excellent agreement.

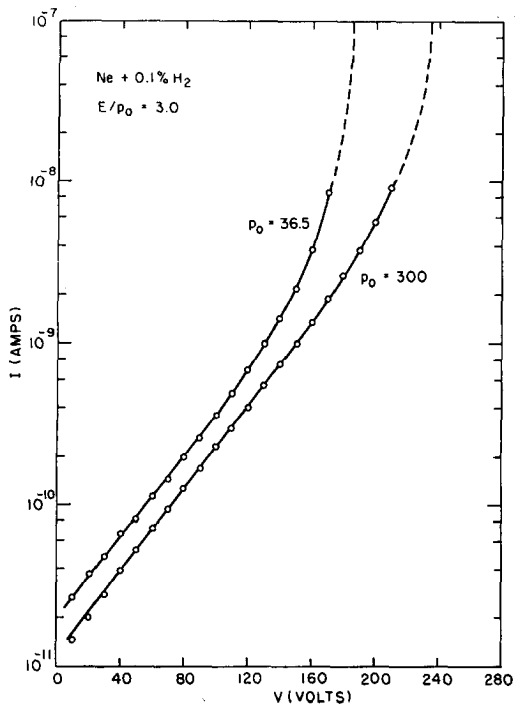

FIG. 1. Examples of ln I vs V curves obtained at low E/p_0 values. The curves shown were measured for Ne+0.1% H_2 mixtures at total gas pressures of 36.5 Torr and 300.0 Torr for the case of $E/p_0=3.0$.

dent, the total variation of the breakdown potential with pressure exceeds the estimated error by a significant amount.

II. APPARATUS

The apparatus used in the present studies has been described in detail previously.[7] In the present measurements the high-vacuum gas-handling station was modified to incorporate high-pressure steel tanks of premixed gas. This step was taken for convenience in the high-pressure measurements >200 Torr. Measurements made on the premixed gas samples were found to be in excellent agreement with samples mixed directly on the gas-handling station. Previous studies of γ using this method have shown that the magnitude of γ is dependent on a number of factors including the type of cathode and the condition of the cathode surface. In the present work no special cathode-cleaning procedures were employed other than the standard high-vacuum techniques; thus, only relative values of γ were considered meaningful.

In the course of the measurements, a number of checks were made to determine if the observed pressure variations were instrumental in origin. For example, Kruithof and Penning[4] reported an $I(0)$ variation with electrode separation due to back reflection losses through their anode. In the present work, measurements of this effect showed it to be entirely negligible. Measurements were also made to determine if η or γ were dependent on the value of $I(0)$; a change in $I(0)$ of approximately one hundred was found to have no observable effect on the measured η and γ values. Thus, in the present measurements where $I(0)$ was typically $\sim 10^{-12}$ A/cm^2, no evidence was obtained which indicated spurious γ values resulting from space-charge distortion. Such an effect has previously been reported by Posin[8] for the case of large electrode separations ~ 5 cm. In the present studies the maximum separation used was approximately 1.9 cm. The short wavelength limit of radiation from the photoelectron-initiating ultraviolet source, normally approximately 1800 Å, was increased to, approximately, 2500 Å. The resulting η and γ values were found to be in extremely close agreement with the previous values.

III. RESULTS

In the course of previous measurements of the primary ionization coefficient in neon–hydrogen and helium–hydrogen mixtures,[2] η was found to be a maximum for E/p_0 values of 3.0 and 15.0 V/cm×Torr, respectively, and for hydrogen concentrations of 0.1%. Previously Kruithof and Penning[9] observed a maximum value of η in neon–argon mixtures for $E/p_0=3.0$ V/cm×Torr

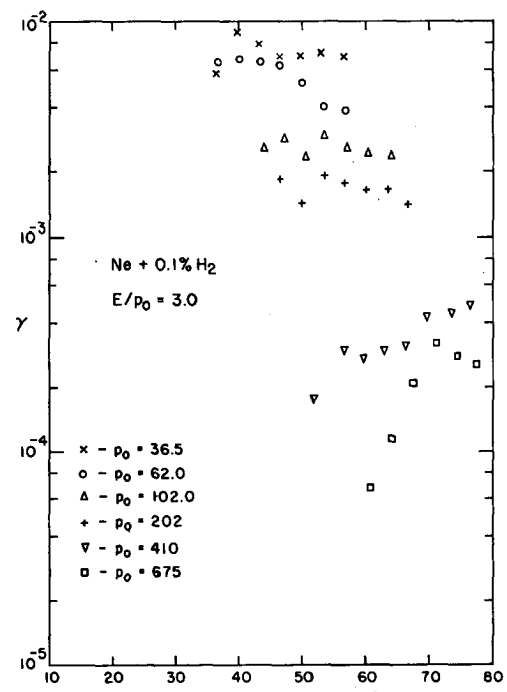

FIG. 2. The variation of γ as a function of relative collision number for various total gas pressures for the case of Ne+0.1% H_2 for $E/p_0=3.0$. For the purpose of clarity only data obtained at certain pressures have been included.

[7] L. M. Chanin and G. D. Rork, Phys. Rev. 132, 2547 (1963).

[8] D. Q. Posin, Phys. Rev. 30, 650 (1936).

[9] A. A. Kruithof and F. M. Penning, Physica 4, 430 (1937).

and for an argon concentration of 0.1%. The agreement between the E/p_0 values corresponding to the maximum of the Penning effect for neon–hydrogen and neon–argon mixtures is to be expected since the effect is primarily determined by the metastable states of the major gas component. In the present work it was decided to investigate the breakdown potential vs pressure variation for all three Penning mixtures at E/p_0 values and minor constituent concentrations corresponding to the maximum of the Penning effect. The investigation consisted of measuring simultaneously η, γ, and the breakdown potential over as wide a range of pressure as could conveniently be studied.

Figure 1 shows an example of the $\ln I$ vs V curves obtained at low E/p_0 in the present studies. The curves given in Fig. 1 were obtained for total gas pressures of 36.5 and 300.0 Torr for the case of Ne+0.1% H_2 for $E/p_0=3.0$ V/cm×Torr. It will be noted that both curves have the usual Townsend characteristics, a linear region followed by a curved portion which increases asymptotically to a breakdown potential value. The difference between the asymptotic values is clearly evident.

Previous measurements of the efficiency function[7] η have shown that useful information can be obtained by measuring the variation of η along a given $\ln I(V)$ vs V curve. The measurements consisted of measuring a sufficiently large number of current values as a function of V for a given E/p_0 to enable one to perform a number of three-point calculations and thus determine the variation of η as a function of p_0x. Such information has proven useful in determining whether or not for a given E/p_0 value, the electrons are in equilibrium with the applied electric field. In the present studies this procedure was followed both for the measurement of η and γ. Since it has been previously shown that the accuracy of measuring these coefficients depends on the choice of ΔV, the values ΔV were maintained constant for a given mixture in order not to introduce any artificial trends in the measurements.

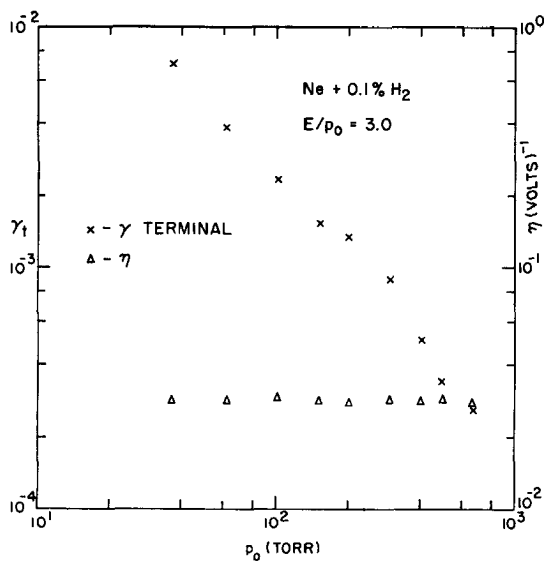

FIG. 3. The variation of η and γ as a function of total gas pressure for the case of Ne+0.1 % H_2 for $E/p_0=3.0$. The terminal values of $\gamma(\gamma_T)$ correspond to those obtained in the strongly curved region of the $\ln I(V)$ vs V curves. The values of η were found to be essentially independent of collision number.

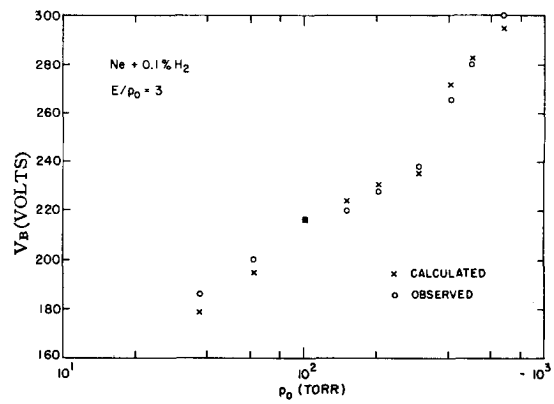

FIG. 4. Observed breakdown potential variation with pressure for the case of Ne+0.1% H_2 for $E/p_0=3.0$. Also shown are the values calculated assuming the Townsend breakdown criterion was valid.

Figure 2 shows a plot of measured γ values as a function of p_0x (proportional to the relative electron collision number) for the neon–hydrogen mixture. The values shown for various total gas pressures were obtained at the optimum conditions for this mixture, $E/p_0=3.0$ and hydrogen concentration of 0.1%. For the purpose of clarity data obtained at all the pressures investigated are not shown in Fig. 2. Calculations were also made of the corresponding behavior for the efficiency function η. While in some cases the values of η indicated a variation with p_0x, the values always varied about an equilibrium value; thus no significant trends with either p_0x or p_0 were observed.

Figure 3 shows a plot of the terminal values of $\gamma(\gamma_T)$ as a function of total gas pressure for the case of neon–hydrogen mixtures for $E/p_0=3.0$. The terminal values are those corresponding to the maximum collision number for a given pressure (in the sharply up-curved region of the $\ln I$ vs V curves). Also shown in Fig. 3 are the corresponding values of η. Clearly from Fig. 3 it will be observed that γ_T decreases strongly with increasing pressure. In contrast, the values of η are constant within the experimental errors.

By measuring the breakdown potential through extrapolation of the $\ln I$ vs V curve to its asymptotic value, it should be noted that this assumes the validity of Eq. (1) over the entire voltage range up to and including the breakdown potential. Having measured the values of η and γ_T as a function of total pressure, it is of interest to provide a check on the consistency of our assumptions by inserting these values into the Townsend breakdown criterion which we assume describes the

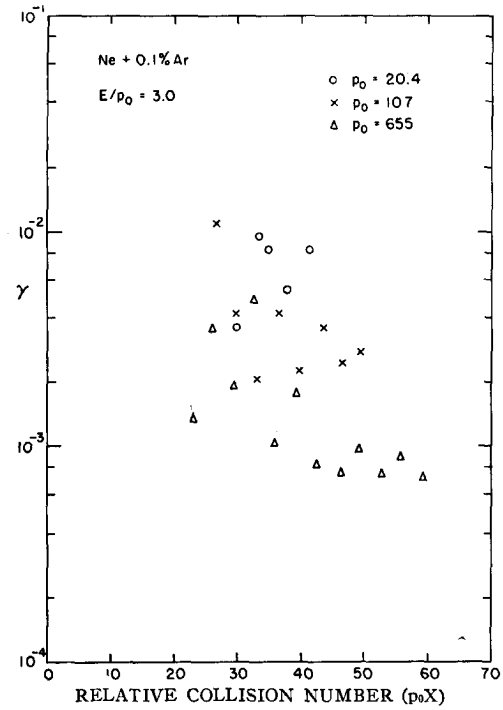

FIG. 5. The variation of γ as a function of relative collision number for various total gas pressures for the case of Ne+0.1% Ar for $E/p_0=3.0$. Only a portion of the total data obtained is shown.

initiation of the breakdown mechanism.[10] This criterion is given by

$$V_B=(1/\eta)\ln(1/\gamma+1), \tag{4}$$

where V_B is the breakdown potential. Figure 4 shows a plot of the observed breakdown potentials as a function of total gas pressure, together with the values calculated[11] using Eq. (4). From Fig. 4 it will be noted that in view of the errors associated with the measurement of V_B the calculated values are in satisfactory agreement with the observed values. Similar agreement was also obtained when the observed values were compared with those calculated from the breakdown criterion for the neon–argon and helium–hydrogen mixtures. Clearly this agreement is to be expected since both the measured and calculated values involve the assumption of the validity of the Townsend mechanisms.

Figure 5 shows a plot of the variation of γ with p_0x for various pressures for neon–argon mixtures at $E/p_0=3.0$ and for 0.1% argon. As in Fig. 2, for the purpose of clarity, only a portion of the total data obtained at various pressures is shown. As in the neon–hydrogen mixture it can be observed that for a fixed collision number, γ appears to be a relatively strong function of the total pressure. As in the previous mixture, measurements of η were made as a function of collision number for all pressures investigated. As before it was found that η was independent of pressure. Figure 6 shows a plot of the γ_T values, and also the values of η as a function of total pressure, obtained for the neon–argon mixture. Figure 7 shows a plot of the observed breakdown potential values as functions of p_0 for this mixture.

Figure 8 shows a plot of the variation of γ with p_0x for various pressures for the case of He plus 0.1% hydrogen for $E/p_0=15.0$. Figure 9 shows a plot of the γ_T values as a function of pressure obtained for this mixture at $E/p_0=15.0$. Also shown in Fig. 9 are the values of η obtained for the corresponding conditions. In this mixture, since the maximum of the Penning effect corresponds to $E/p_0=15.0$, the maximum pressure values which could be investigated were considerably less than for the neon–hydrogen and neon–argon mixtures. Figure 10 shows the measured breakdown potential values for this mixture.

In the present work, curve fitting was attempted in several ways for cases in which a pronounced variation of γ with p_0x had been observed. In particular, the values of γ used were: (1) assumed constant, here the value was obtained by averaging the values obtained at various p_0x values; (2) assumed constant, here γ was calculated from the breakdown criterion using measured values of η and V_B (this method has often been used in the past by previous investigators); (3) assumed variable, here

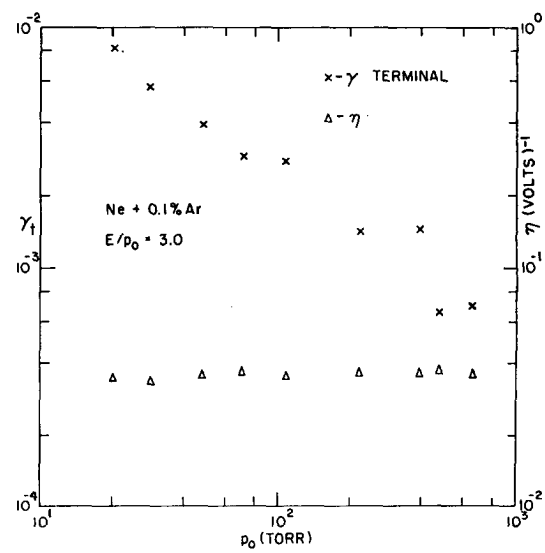

FIG. 6. The variation of η and γ as a function of total gas pressure for the case of Ne+0.1% Ar for $E/p_0=3.0$. The values of γ are the terminal values (γ_T) corresponding to the maximum collision number. Values of η were found to be essentially independent of collision number.

[10] Numerous discussions have appeared in the literature (see, for example, Ref. 3) concerning the validity of the breakdown criterion. The generally accepted view at present is that in many cases at threshold, breakdown in uniform fields is initiated by a low-order Townsend discharge leading to breakdown by space-charge formation. Assuming the breakdown criterion is valid amounts to the assumption that the difference between the value of the applied field in which space-charge distortion becomes apparent and the breakdown field is so small that Eq. (4) represents a good approximation for breakdown.

[11] For the purpose of estimating V_B from the breakdown criterion we have neglected the value of V_0. While the exact values of V_0 are not well known in general they appear to be comparable to the ionization potential (see Ref. 4) for the case of a pure gas.

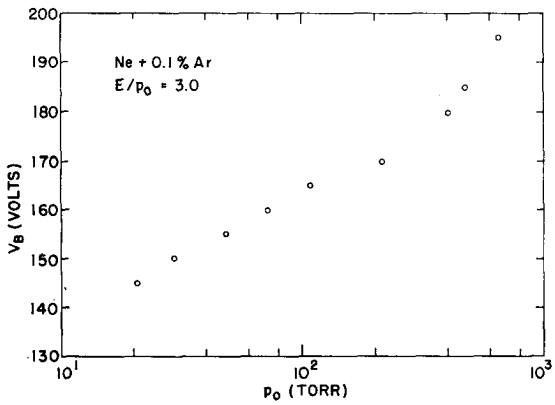

FIG. 7. Observed breakdown potential variation with pressure for the case of Ne+0.1% Ar for $E/p_0=3.0$.

values of γ were used appropriate to the measured p_0x range. In summary, using the first assumption, poor agreement was obtained between the experimental $\ln I$ vs V curve and that calculated from Eq. (1). Better agreement was obtained using the second assumption particularly for large voltage values. Finally, using the third assumption, excellent agreement was obtained over the entire curve with the exception of very small voltage values where the electrons were not in equilibrium with the field and hence Eq. (1) was not valid. Clearly this last result was not unexpected but only served to check the consistency of the results.

IV. DISCUSSION OF RESULTS

From Fig. 2 it can be observed that in the neon–hydrogen mixture, starting at the lowest pressures, with increasing p_0x, the values of γ are relatively constant with a slight downward trend in the values apparent. At very high pressures, however, $\gtrsim 400$ Torr, it will be noted that in contrast the γ values increase with p_0x. While this behavior was not apparent for the neon–argon mixture, a similar variation can be noted in Fig. 8 for the case of the helium–hydrogen measurements. The marked change in the behavior of γ with p_0x from low to high pressures suggests the possibility that there is a pronounced change in the process contributing to γ.[12] In the course of the measurements tests were made to determine whether the observed variation of γ could be accounted for on the basis of changes in the cathode surface conditions. Thus measurements were made at random pressures to determine if the corresponding values fit the observed pressure variation. In every case agreement was obtained, suggesting that the results could not be accounted for on the basis of cathode surface changes. As previously noted Eq. (1) was derived assuming that η and γ were independent of V. The fact that differential measurements of γ clearly indicate that γ varies along the growth of the $\ln I$ vs V curves and hence depends on V can be reconciled with this assumption, since by using Eq. (3) which is derived from Eq. (1) it is only necessary to assume γ is constant over the ΔV range considered.

In an attempt to account for the variation of γ with pressure we investigated the variation of $I(0)$ with pressure for a fixed E/p_0 value, and on a given day so that the value of $I(0)$ *in vacuo*, and the cathode surface conditions remained as constant as possible. On the basis of simple back diffusion theory[13] one would expect the back diffusion losses to be independent of pressure for a fixed E/p_0 value. The validity of this picture appears to have been confirmed[14,15] on several occasions. In the present results, however, for example in the case of the neon–hydrogen mixture, we observed a decrease in the values of $I(0)$ with increasing pressure of approximately 2.7 over the entire pressure range studied. As previously indicated $I(0)$ values inferred from extrapolation to $V=0$ or calculated using Loeb's equation were identical.

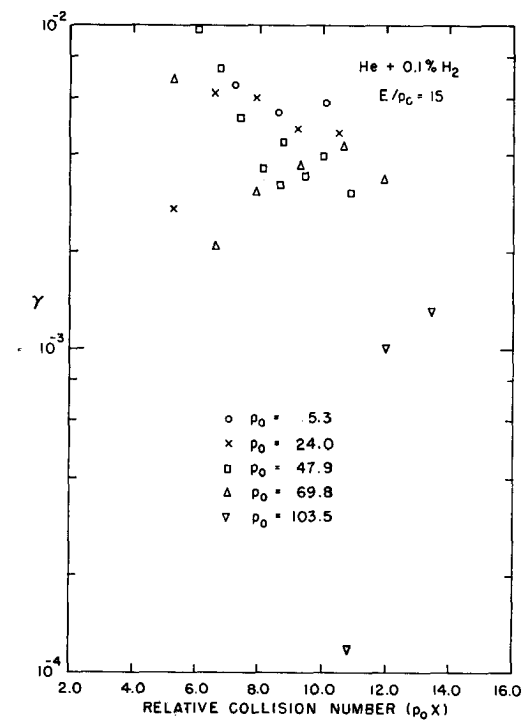

FIG. 8. The variation of γ as a function of relative collision number for various total gas pressures for the case of He+0.1% H_2 for $E/p_0=15.0$.

[12] The present results for γ and V_B do not conform with the principle of similitude and Paschen's law. Paschen's law states that the breakdown potential V_B is a function only of the product of the electrode separation and the pressure. Hence for a given value of p_0x, V_B should possess a single value. If, however, we accept the definition of the breakdown potential as being $V_B=(\eta)^{-1}\ln[(\gamma)^{-1}+1)]$, the present results which show that η is single valued, also indicate a range of γ values (depending on the value of p_0), thereby leading to multiple values of V_B and hence a violation of the law.

[13] J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge University Press, Cambridge, England, 1928).

[14] J. K. Theobald, Phys. Rev. **24**, 123 (1953).

[15] D. K. Davies, J. Dutton, and F. Llewellyn Jones, Proc. Phys. Soc. (London) **72**, 1061 (1958).

It is to be noted that the value of γ decreased by a factor of 30 over the same pressure range. Thus it is apparent that the observed variation of $I(0)$ with pressure cannot account for the observed γ variation. Similar conclusions apply to the cases of neon–argon and helium–hydrogen mixtures. The reason for the variation of $I(0)$ with pressure is not understood; apparently, the simple back diffusion theory is not valid over a wide range of pressures.

Over the years a number of discussions[16] have appeared in the literature concerning limitations of the Townsend technique for measuring the secondary coefficient γ. Of these criticisms, the principle arguments have been concerned with the lack of adequate control of surface conditions and the fact that such measurements only provide an averaged value in which the relative contributions of various processes to γ cannot easily be evaluated. Clearly the present results are susceptible to these criticisms. While in the present work evidence was obtained which indicated that the cathode surface conditions remained relatively constant, it is clear that the significance of the absolute values of γ is somewhat uncertain because of the unknown condition of the cathode surface. Pressure-dependent secondary coefficients have previously been reported by a number of investigators. Lauer[17] reported a photon coefficient in hydrogen which decreased an order of magnitude in going from 100 to 650 Torr for E/p_0 values of 1.43 and 0.66, respectively. Photon absorption was believed to be responsible for this effect. Hopwood,

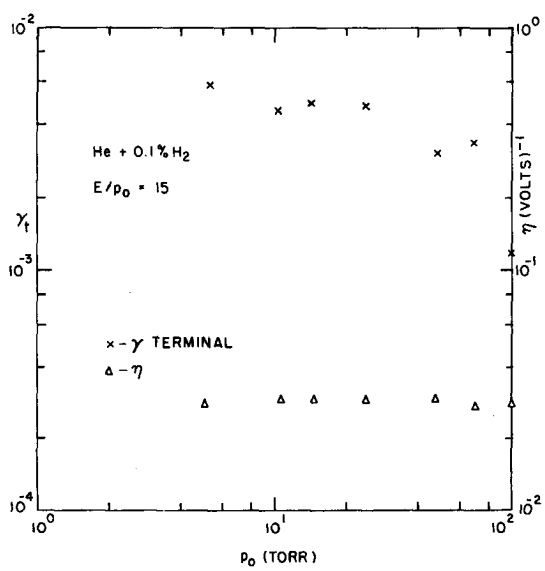

FIG. 9. The variation of η and γ as a function of total gas pressure for the case of He+0.1% H_2 for $E/p_0=15.0$. The values of γ are the terminal values (γ_T) corresponding to the maximum collision number. Values of η were found to be essentially independent of collision number.

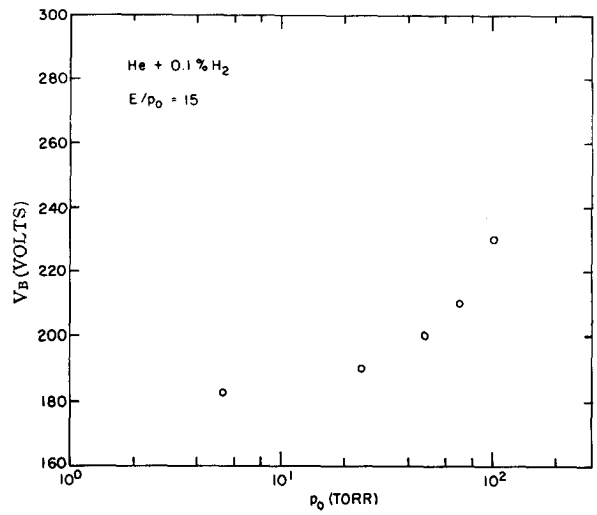

FIG. 10. The observed breakdown potential variation with total gas pressure for the case of He+0.1% H_2 mixtures for $E/p_0=15.0$.

Peacock, and Wilkes,[18] studying breakdown in hydrogen for E/p_0 values between 18 and 28, observed a decrease in γ by a factor of approximately four when the total pressure was varied from 100–700 Torr. No explanation was advanced to account for the observed variation. Davies, Dutton, and Llewellyn Jones,[15] studying secondary ionization processes in hydrogen for $E/p_0=20$ V/cm×Torr, reported a decrease in γ of approximately a factor of two as the total pressure was changed from approximately 250–450 Torr. These authors concluded that their observations could be accounted for on the assumption that the secondary ionization was predominantly of photoelectric origin and that destruction of excited molecules occurred by collisions of the second kind, thereby diminishing photon production.

It is generally agreed that the total measured γ may consist of contributions by metastable atoms, positive ions, and photons. In the present results the possibility of metastable contributions may be dismissed since the measurements were performed at the maximum of the Penning effect. Under these conditions metastable deactivation by the minor constituent is at an optimum; hence, very few metastables are believed to be present. Moreover, such an effect should influence the primary coefficient. In this respect the present results indicate that the hypothesis of Frouws[1] to account for his observed variations of the breakdown potential with pressure at fixed p_0x by means of three-body destruction of metastables is invalid for low E/p_0 values. While the case of the Penning mixture at low E/p_0 is different compared to that of a pure gas, in that appreciable ion production results in the mixture, the present data suggest that the major contribution to γ does not result

[16] See, for example, L. B. Loeb, Ref. 3, Chap. 9.
[17] E. J. Lauer, J. Appl. Phys. 23, 300 (1952).
[18] W. Hopwood, N. J. Peacock, and A. Wilkes, Proc. Roy. Soc. (London) A235, 334 (1956).

from positive ions. Thus reference to Fig. 2 clearly indicates that the value of γ for a fixed collision number is a strong function of the total pressure. If, for example, ionic conversion were responsible for the γ pressure variation, one would expect that γ should be a function of p_0x and not of total pressure. Finally, even if one hypothesized a change of ionic species, previous measurements by Hagstrum[19] indicate that in the noble gases the γ values resulting from ion bombardment are only slightly different for the atomic and molecular ions. Thus, a change of ionic species would seem unlikely to account for the magnitude of the observed variation. It would thus appear that the primary contribution to the γ values measured in the present experiment must result from photons.[20] In their studies of γ in hydrogen, Davies, Dutton, and Llewellyn Jones[15] obtained an expression for γ of the form

$$\gamma=\gamma_0\{1-\tau\nu P(d)\}. \tag{5}$$

This equation was derived assuming that destruction of excited states by collision could account for their observed pressure variation of the secondary coefficient. Here τ referred to the lifetime of the excited state which subsequently could give rise to the emission of photons, ν was the collision frequency of the excited states with neutral particles, $P(d)$ referred to the probability of destruction of the excited states in collisions of the second kind and γ_0 was a constant for a given E/p_0 and p_0x value. On the basis of Eq. (5) these authors concluded that a linear dependence of γ on pressure would be expected. This result was in accordance with their experimental observations. It is to be noted that a linear pressure dependence results from Eq. (5) only if $P(d)$ is pressure independent. In the present results a simple linear dependence was not observed for any of the mixtures investigated. Assuming Eq. (5) is valid and $P(d)$ is pressure independent, γ should be a linear function of the collision number. As previously noted from Figs. 2 and 5, in general, γ is not primarily a function of collision number but rather of the total pressure. From these considerations we conclude that the present results cannot be accounted for on the basis of destruction of excited states. One of the more likely explanations for the observed results is that of photon absorption. Current studies[21] in Townsend discharges have clearly demonstrated the importance of this effect. The present results could be accounted for if Beer's law were not valid under the present experimental conditions.[22] Clearly, the present technique does not provide sufficient details concerning the basic γ mechanisms to provide a satisfactory explanation.

In the course of the present work, measurements of η, γ, and V_B were also conducted in all three mixtures at $E/p_0=100$. In general, the breakdown potential was observed to decrease with increasing pressures in contrast to the behavior at low E/p_0 values. Here both η and γ were observed to be functions of p_0x and also p_0. Under these conditions the electrons were not believed to be in equilibrium with the applied electric fields. While in the case of the neon–hydrogen mixtures rough agreement was obtained between the calculated and observed breakdown potentials, for the neon–argon and helium–hydrogen mixtures very poor agreement was obtained. In general, for $E/p_0=100$ in all the mixtures the current growth behaved quite differently than at low E/p_0. Thus, while a short upcurved region was observed, this region would terminate in an abrupt transition to a high-current level. Clearly, under these conditions the Townsend equation would not properly describe the growth pattern, and thus accounts for the fact that attempts to correlate the measured η and γ values with the observed breakdown potentials were unsuccessful.

In addition to the measurements in the mixtures, previous data obtained in pure helium and pure neon were reanalyzed at low and high E/p_0 (10 to 100) to determine if the secondary ionization coefficient were pressure dependent. To summarize the results, no significant dependence was observed; however, the ranges of pressures covered at low E/p_0 were considerably less than those studied in the mixtures. For $E/p_0=10$ the pressure varied only by a factor of three; at $E/p_0=100$ the range was approximately a factor of twenty. For the case of hydrogen at $E/p_0=100$ no significant variation of γ was observed for gas pressures ranging between 4.0 to 16.0 Torr. Finally, it is interesting to note that for the pure gases the value of γ in general increased by at most a factor of two in going from low to high E/p_0 values. However, for the case of the gas mixtures, in general, γ increased at least an order of magnitude from low to high E/p_0 values. Moreover, for the case of the gas mixtures the value of γ was more nearly typical of that of the minor constituent than of the major component. This behavior is to be expected for the case of a Penning mixture since the majority of the excitation is, by definition, transferred to the minor constituent.

V. CONCLUSIONS

At the optimum of the Penning effect, on the basis of the well-behaved experimental current growth curves and assuming the validity of the Townsend mechanisms up to the breakdown potential, the breakdown potential

[19] H. D. Hagstrum, Phys. Rev. **91**, 543 (1953).

[20] The contribution of photoionization processes in electrical breakdown has been discussed by several investigators; see for example L. B. Loeb, Brit. J. Appl. Phys. **3**, 341 (1952); J. Dutton, S. C. Haydon, and F. Llewellyn Jones, Proc. Roy. Soc. (London) **A218**, 206 (1953). Loeb has shown that whether or not the photoionization contribution affects the primary or the secondary process is dependent on the relative magnitudes of the absorption and the primary coefficients.

[21] G. R. Govinda Raju, J. A. Harrison, and J. M. Meek, *Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, 1963* (North-Holland Publishing Company, 1964), VA35, p. 197.

[22] D. R. Bates, *Atomic and Molecular Processes* (Academic Press Inc., New York, 1962), p. 83.

at fixed E/p_0 was observed to increase with increasing gas pressures. The present results further indicate that at fixed E/p_0 the primary ionization coefficient was independent of total gas pressures in contrast to the behavior of the secondary coefficient which decreased with increasing pressures. Thus the variation of the breakdown potential was believed to result from the pressure variation of the secondary coefficient. Reasons for the behavior of the secondary coefficient are not clear; however, photon absorption processes seem to be a likely possibility.

Measurements for $E/p_0=100$ (well beyond the maximum of the Penning effect) also indicated a pressure dependent breakdown potential. However, under these conditions the Townsend mechanisms did not appropriately describe the growth to the breakdown condition.

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Laser-Induced Thermionic Emission from Tantalum*

C. M. Verber and A. H. Adelman
Battelle Memorial Institute, Columbus, Ohio
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We have measured the induced thermionic emission of electrons from tantalum as the result of bombardment with laser beams of up to 10^5-W/cm^2 peak power density as a function of the tantalum temperature. It is shown that within the power range investigated, the results can be described in detail as thermionic emission resulting from a temperature increase which is calculable from classical heat-transfer theory.

INTRODUCTION

It has been demonstrated by a number of investigators,[1–4] that copious electron emission can result from the bombardment of a metal surface by a laser beam. In particular, it has been suggested that some of the observed emission effects could be explained as being due to thermionic emission. Contradicting our statement in a previous paper[2] that the signal could not wholly be explained by thermionic emission, it is shown in the more detailed treatment given below that for laser powers at least as high as 10^5 W/cm^2, the amplitudes, the gross shape, and the dependence of the induced emission signal upon the laser power and upon the target temperature can be predicted in great detail by thermionic emission. The emission occurs as the result of a surface temperature increase which can be calculated from classical heat transfer theory. It should be pointed out that, at higher power densities, effects exist which may not be fully explained by this mechanism.[4]

HEAT-TRANSFER CALCULATIONS

The problem of the pulsed heating of a semi-infinite solid has been discussed by Jaeger[5] for the case in which the heat pulse was applied uniformly to the entire surface and the case in which the heat pulse was limited to pulses which have a rectangular time dependence.

For the case of a less regular pulse whose time dependence cannot be expressed by any convenient analytic function, a useful solution for the temperature of a semi-infinite solid irradiated uniformly over its surface can be obtained by following the standard Laplace transform method. The heat conduction equation to be solved is

$$\frac{\partial^2 u(t,x)}{\partial x^2}-\frac{1}{\alpha}\frac{\partial u(t,x)}{\partial t}=0, \tag{1}$$

with the temperature $u=0$ when $t\leq 0$ and the boundary condition

$$-K(\partial u/\partial x)=f(t) \tag{2}$$

when $x=0$. Here x is the depth of the solid as measured from the surface, $f(t)$ is the flux of heat incident upon the surface expressed in cal/cm^2-sec, α is the thermal diffusivity, and K the conductivity.

The transforms of Eqs. (1) and (2) are

$$(\partial^2 U(s,x)/\partial x^2)-(s/\alpha)U(s,x)=0$$

and

$$-K(\partial U/\partial x)=F(s)$$

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