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SHORT COMMUNICATION

Mechanism of Negative Space Charge in Gas Subjected to Corona Discharge

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ABSTRACT

The currents produced by low frequency electrodeless discharge of ozoniser filled with argon at $P = 10$ mm mercury have been measured using a galvanometer actuated by the crystal rectifier and a resistor of 500 ohm. The measurements have also been made simultaneously with the help of electronic scaler. The data are presented graphically by the plots of current against potential. A change in slope of the curves for a pulse height of 5 V has been attempted on the basis of space-charge-limited current and mathematically formulated equation, viz., $I = A'.V.\Delta V_o$; where A' is a constant of proportionality and is equal to $2K/C.P.\pi.R^2_{ow} \log(R_{ow}/R_{iw})$, which can be determined from the known values of reduced mobility of the ions of the space charge (K); the pressure (P); the radii of outer (R_{ow}) and inner(R_{iw}) cylinders and the over voltages, (ΔV_o). A side by side measurement of the light effect, ie, change $\pm \Delta I_g$ in the discharge current due to external irradiation, revealed to definite dependence of sign and magnitude of the ΔI_g on the potential in the system studied. Thus, on irradiation of the discharge by light from a 15 W tungsten filament clear glass bulb, at low potentials [below the first threshold potential of argon, (V_g)], there was practically no variation in the current, while at higher potentials, at and above V_g, the current was completely enhanced. Further, a few ramifications related to defence, of such instantaneous and reversible photo-variation of discharge current due to radiation, are also described.

Keywords: Corona discharge, space charge, space-charge-limited current, discharge current, radiation effect, space-charge-free region, space-charge-limited regime

NOMENCLATURE

Ar	Argon
P	Pressure
HT	High tension
LT	Low tension
A	Atomic weight
A'	$2K/C.P.\ \pi.\ R^2_{ow} \log[R_{ow}/R_{iw}]$ = A constant
K	Reduced mobility of the ions of space charge
R_c	Radius of collector
R_{iw}	Radius of inner cylinder of the ozoniser
R_{ow}	Radius of outer cylinder of the ozoniser
r_u	Radius of the zone of intense ionisation
$d = dr$	Distance between the electrodes
m & e	Mass and charge of an electron
M	Mass of positive ion
n	Number density of primary electrons

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L Length of cylinder

ΔV_o Over voltage is equal to difference between applied voltage V and peak voltage V_p

V_r Reduced potential

α Number of new ion pairs created per electron per cm in the field direction

β A coefficient to be taken from the data given by Langmuir and Compton

I Space-charge-limited current between peak voltage V_p and valley voltage V_v

I_{gD}, I_{gL} Discharge currents in dark and under irradiation, usually in milliampere units of galvanometer scale deflection

I_{sD}, I_{sL} Discharge currents in darkness and under irradiation, usually in arbitrary units of a counter scaler

$\frac{1}{2} mv_2^2 - \frac{1}{2} mv_1^2$ Difference in kinetic energies of an electron in vacuum

$\frac{1}{2} Mv_2^2 - \frac{1}{2} Mv_1^2$ Difference in kinetic energies of a positive ion

$V_1 - V_2$ Difference of potentials

v_2 Velocity of electron at a point 2 or velocity of positive ion

v_1 Velocity of positive ion at a point or velocity of electron at a point 1.

$$\left.\begin{aligned} -\Delta I_g &= I_{gL} - I_{gD} \\ +\Delta I_S &= I_{SL} - I_{SD} \end{aligned}\right| \text{Net effect of light}$$

1. INTRODUCTION

Studies[1] of the influence of ionic space charge on the light effect showed that even in chlorine, the conductivity of the discharge and the light effect depend on the space charge of positive ions rather than that of negative ions. During the studies of light effect over a wide range of pressures and potentials in hydrogen, which has a very low electron affinity, the discharge current appeared to rise as a parabolic function of the applied voltage[2]. The results of these studies have been explained by assuming the space-charge-limited region over a certain range of voltage. In his earlier studies, the author[1,3] had also assumed the existence of positive ionic space charge to explain the production of high frequency pulses under silent electric discharge and the light effect. He found that for voltage near the breakdown potential (V_p), space charge is not active. It was, therefore, considered of interest to investigate the potential at which the space-charge-free region changed over to a space-charge-limited regime, as the potential was increased. An attempt has been made to correlate the negative and the positive space charges with an almost instantaneous and reversible photo-variation of discharge current in argon under electrical discharge due to external radiation. Such an effect of radiation can possibly be, linked with the defence, attributed in controlling the following different reactions:

(a) The light effect can be applicable for studying the course of even a homogeneous gas reaction since the characteristic (ionic and molecular) species form boundary layer, the main seat of the light effect.

(b) It is, however, readily and directly applicable for the solid-state reactions of the more chemical type-explosive, Smekal-type chain reactions.

2. EXPERIMENTAL PROCEDURE

A degassed and aged[4] Siemen's-type ozoniser made of quartz glass filled with argon at a definite pressure of 10 mm mercury was used in this investigation. The experimental arrangement was more or less the same as described earlier[5].

A constant voltage transformer was used for maintaining a steady potential to the primary of the high tension transformer, from which a secondary potential of the required voltage was obtained, by means of a dimmerstat included in the primary circuit. A probe of the step-up transformer was immersed in the inner tube of the vessel containing a salt solution as an electrolyte and the other was grounded. The outer terminal of the vessel, immersed in the glass beaker containing the same electrolytic solution, was connected to the primary circuit of a bell-type transformer. A counter scaler was connected across a resistance of 470 ohm included serially in the primary circuit of this transformer and the earth. A reflection galvanometer, shunted by a resistance of 600 ohm, was used with a crystal rectifier and a resistance of 500 ohm to measure the average current through the secondary of the bell-type transformer. The general setup of apparatus and electrical circuit are shown in Fig. 1.

2.1 Some Remarks on Data Collection

The measurements[1] of count rate (I_S) with an electronic scaler[2] and of current (I_g) with the help of mirror galvanometer were made simultaneously in dark and under visible radiation obtained from a 15 W incandescent glass lamp placed at 30 cm from the experimental vessel. The discharge currents I_S and I_g are given in arbitrary units and in milliamperes, respectively, but all the results obtained from the measurements of the later detector are computed in their respective units, using the currents in amperes. Thus, data collected on the potential variation of discharge current in dark and under light are presented graphically in Fig. 2.

3. RESULTS & DISCUSSION

3.1 Interpretation of Current-voltage Curves

In the Fig. 2, there is a set of curves in dark and under light at P = 10 mm mercury and at a definite pulse amplitude of 5 V. Curves I to III in Fig. 2 show that when the applied field exceeds 1.4 kV and 1.7 kV [r.m.s], the current rises. This range extends up to the field of about threshold potential as a separable region. In this region, the number of new electrons and ions created by one electron in progressing a distance in alternating current field is expressed as

$$\int_{r_u}^{R_{iw}} \alpha.dr$$

where α denotes the number of new ion pairs created per electron per centimeter in the field direction. The integral yields the total ionisation and represents the number of electrons that arrive from the radius of some of intense ionisation to the inner electrode (high tension), ie, from r_u to R_{iw}. The positive ions created in an avalanche remain essentially at rest during the creation of the avalanche, since the electrons move faster than the ions. The current density (J) at the inner high tension electrode in the non-self-sustained region can be expressed as

$$J = n.e.\exp \int_{r_u}^{R_{iw}} \alpha.dr \tag{1}$$

where n is the number density of the primary electrons of charge (e), dr is the separation between the electrodes, and

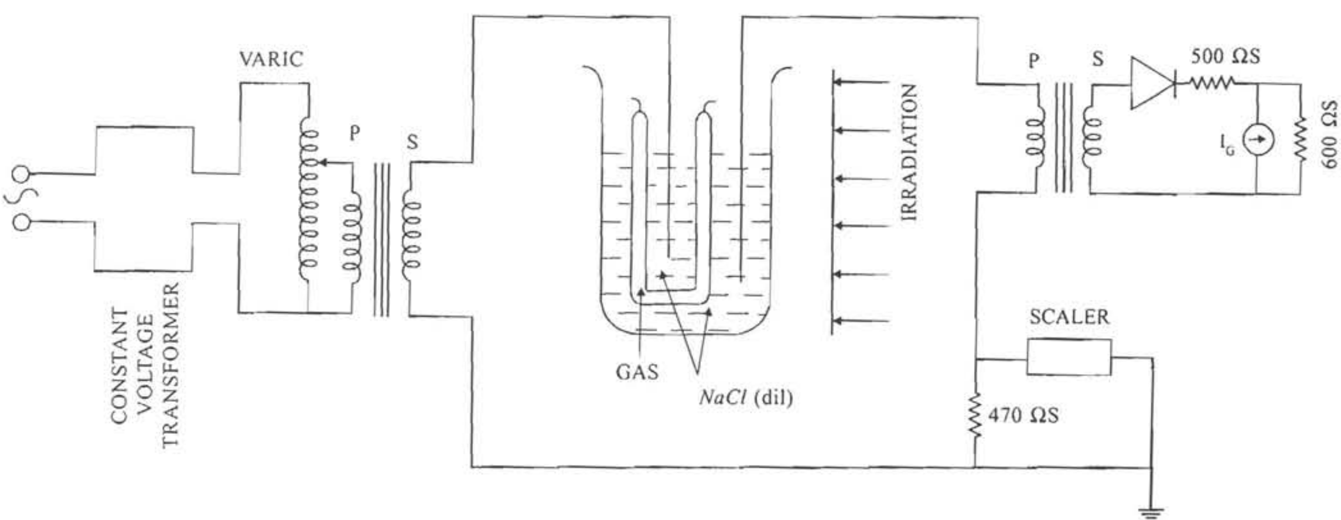

Figure 1. Experimental arrangement to obtain negative and positive characteristics of voltage-current curves on a galvanometer and a scaler.

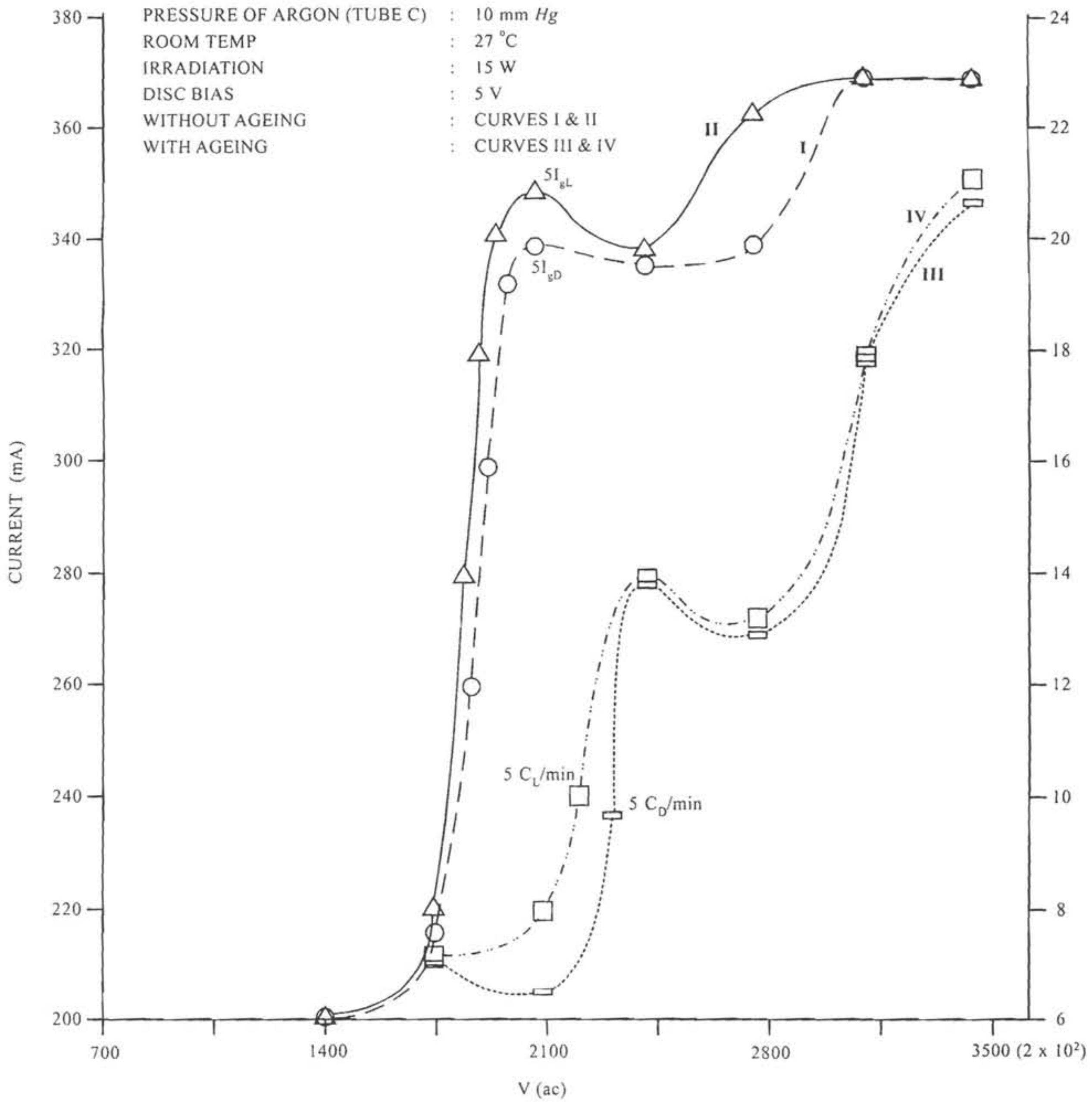

Figure 2. Comparison of current emission in argon tube C measured for an amplitude of 5 V

$$\int_{r_u}^{R_{iw}} \alpha . dr$$

is the exponent.

The value of this exponent can be fixed by the primary process of ionisation and excitation by electron impact, and this value is largely dependent on the gas type and field geometry. Thus, small changes in an exponent compensate for a large variation in the secondary action. This renders the threshold potential very active to primary action and not sensitive to secondary action. Furthermore, most of the ionisation needed for maintaining a given current being known to be completed within a critical distance. This critical distance and not the full electrode distance is relevant to stabilise the current density as implied by the equation of

$$J = n.e. \exp\left[(R_{iw} - r_u)\alpha\right] \quad (2)$$

With white light, a curve II in Fig. 2 shows an unmistakable current increase [$+\Delta I_g$] at 2.1 kV [r.m.s.], not to be expected on the general physical theory[6,7] and a current decrease [$-\Delta I_g$] at 2.45 kV [r.m.s.]. This potential-inversion of the currentincrease at lower V to the current decrease at higher V is a definite new result in the electron-free gas [Argon]. The curve IV in Fig. 2 shows the current, measured with an electronic scaler, decrease-ΔI_S[$= I_{SL} - I_{SD}$, where I_{SD} and I_{SL} are the current in dark and under light], respectively, at 2.1 kV [r.m.s.], contrary to a curve II at 2.1 kV [r.m.s.] would be expected from the general physical theory[8]. In this configuration, ion beam is accelerated on either side of the real and the virtual cathode.

3.2 Formation of Negative Space Charge

The total number of electrons emitted by the low tension of discharge vessel actually reaches the high tension or not, is determined by the applied V, as well as by the phenomenon known as space charge. The term space charge, ie, the cloud of electrons, is formed in the space between low tension and high tension. This cloud constitutes a negative charge in the interelectrode space that has a repelling effect on the electrons, being emitted from the low tension. The effect of this negative space charge alone, therefore, is to force a considerable portion of the emitted electrons back into the low tension and prevent others from reaching the high tension.

The space charge, however, does not act alone. It is counteracted by the electric field from the high tension, which reaches through the space charge to attract electrons, and thus, partially overcomes its effects. At the high tension voltages, in the range $V_p < V < V_v$, only electrons nearest to the high tension are attracted to it and constitute less current, compared to a value of current at breakdown potential. The space charge then has a strong effect on limiting the number of electrons reaching the high tension. An interesting expression holds for the discharge vessel that is operated in a region of $V_p < V < V_v$. Its mathematical formulation is as follows:

A space-charge-limited current above the threshold voltage is investigated from the stand point of the 3/2 power law, viz.,

$$I = [1/9\pi]\sqrt{2e/m}(V^{3/2}/d^2) \quad (3)$$

If the distance d between the electrodes is kept constant, then Eqn (1) reduces to the form $I = B\ V^{3/2}$, where

$$B = [1/9\pi d^2]\sqrt{2e/m} \quad (4)$$

This equation was first deduced by Pimpale[3] for ions in an arc. While this is obtained on the assumption that there is no discharge between the electrodes, Thomson[9] had shown that this holds good also when there is a uniform ionisation. Pimpale[10] had further extended this equation for concentric cylinders in which the current (I), assuming negligible velocities of emission, is given by

$$I = [2/9]\sqrt{2e/m}\,[LV^{3/2}/R_C.\beta^2] \quad (5)$$

where R_C belongs to radius of the collector, L the length of the cylinder, and β^2 to a coefficient to be taken from the data given by Pimpale[3,10].

The application of Eqn (5) to the standardised type of vessel consisting essentially of two concentric glass, quartz tubes, depends upon the following two conditions:

(a) The inner electrode surrounded by a space charge sheath of radius R_{ow}.

(b) The change in R_{ow} / R_C and β^2 due to a change in V is negligible because of the large value of the inner cylinder. Pimpale[3] had found that: (i) at high pressure of H_2 and at potentials, the second assumption that β^2 does not change appreciably with a change in V, is not valid, and (ii) that the slope of the double logarithmic plot of V-I curve is nearly 2, instead of 3/2, as expected from the 3/2 power law.

The present data in argon is, therefore, examined from the stand point of the Werner's equation[11], which reads:

$$V[V - V_p] = (\pi.C.P.I/K)\,[(R_{ow}^2 - R_{iw}^2) - (r_u^2 - R_{iw}^2).\,\{\log(R_{ow}/R_{iw})/\log(r_u/R_{iw})\}] \quad (6)$$

where r_u is the radius of the intense zone of ionisation surrounding R_{iw}. The Eqn (6) was derived by Werner[11] in a study of Geiger counteraction. Neglecting R_{iw} compared with R_{ow} and $(r_u^2 - R^2_{iw})$ compared to R^2_{ow}, the Eqn (6) becomes:

$$V[V - V_p] = (\pi.C.P.I.R^2_{ow}/2K).\log(R_{ow}/R_{iw}) \quad (7)$$

which was derived by Pimpale[12] on the same reasoning but with simplified assumptions. Equation (7) can be expressed as

$$I = A'.V.[V - V_p] = A'.V.[\Delta V_o] \quad (8)$$

where A' is a constant of proportionality, and is equal to $[2K/ C.P. \pi. R^2_{ow} .\log(R_{ow}/ R_{iw})]$, which can be evaluated from the reduced mobility of the ions of the space charge (K); the gas pressure (P); radii of outer (R_{ow}) and inner (R_{iw}) cylinders and V_p be the peak voltage.

Therefore

$$\Delta V_o = V - V_p$$

and

$$V_r = \Delta V_o / V_p \quad (9)$$

represents as the over voltage (ΔV_o) and the reduced [corresponding] potential, (V_r) , respectively.

3.3 Neutralisation of Negative Space Charge

If the applied V is raised above V_v, valley potential, the discharge current once again shows a rapid growth. This increase in current can possibly be due to the fact that the electrons are now capable of ionising the gas atoms. From this movement onwards, positive ions as well as electrons move through the gas, and the ions with their positive space charge partly neutralise the effect of the negative space charge of the electrons. The repulsion exercised by the later is mitigated, and thus, more electrons are able to leave the low tension. This fact is an important one, since the mobility of the ions is much slower than that of the electrons. Mathematically, it can be expressed as:

In one and the same electric field, acceleration [force/mass] is much greater for an electron than for an ion. Because of two points with potential of V_1 and V_2, the kinetic energy of an electron in the vacuum increases by

$$\tfrac{1}{2} mv_2^2 - \tfrac{1}{2} m v_1^2 = e (V_2 - V_1) \quad (10)$$

It expresses in electron-volts by the difference of potentials V_2 and V_1. For positive ions, the relation becomes

$$\tfrac{1}{2} Mv_2^2 - \tfrac{1}{2} Mv_1^2 = e (V_1 - V_2) \quad (11)$$

According to these two relations, the ratio of the velocities of electrons and the argon ions, having the same amount of energy, is $\sqrt{M / m}$ [= 73600 for argon], where M, the mass of positive ion with an atomic weight A is 1840 A times as great as m, the mass of an electron, while the energy of the ions is much less than that of the electrons due to collision losses. Thus, one positive ion is able to neutralise the space of hundreds of electrons. This effect is further enhanced by changes that occur in the distribution of potential.

3.4 Effect of External Radiation on the Current Pulses

It is seen from curve II in Fig. 2 that current increases under irradiation. The magnitude of increase depends upon both the intensity and frequency of the radiation. The increase in current under light is reversible, being eliminated when irradiation ceases.

It is well known that light does not cause any significant change in the resistance and capacitance of the glass, on which current depends. Consequently, the only interaction which can possibly explain the increase in current under irradiation seems to be photoemission from the negatively charged glass wall of the ozoniser. The photoemission removes electrons from the negatively charged surface and this causes a decrease in the potential difference in addition to that already produced by the impact of the current pulse. Since the electron removal by photoemission is gradually balanced by the leakage of the charges through the glass wall, the time required to create the potential difference necessary to strike the discharge increases. Because the photo-emission itself depends upon the intensity and frequency of the radiation, current also depends on these two factors. It may be mentioned here that in the case of x-rays and γ-rays, the ejection of Compton electrons from the cathode would play a role similar to photo-emission.

The above interpretation of the observed effect of light on the current is helpful in understanding the phenomenon of the positive effect[13], an almost instantaneous and reversible photo-increase of the current in the gas under electrical discharge due to external radiation. This phenomenon has been reported in numerous gases[2,13] and for irradiation under varying conditions[14].

4. CONCLUSION

The discharge current increases linearly from the initial value to some peak value (I_p) at a voltage (V_p) which is typically 2.1 kV [r.m.s.] in the curves I and II and 2.45 kV [r.m.s.] in the curves III and IV (Fig. 2). Because the application of voltage reduces the electric field strength across the low tension and high tension, the tunnelling current decreases when the applied voltage exceeds V_p. This current-decrease results in a region of negative conductance. Above the valley voltage (V_v), the discharge current predominates and the current increases in usual manner.The system's characteristics exhibit a negative resistance region and may be used as an ultra-fast switching device or in ultra-high frequency oscillators.

As explained above, the number of discharge pulses with irradiation in a given time increases, as a result of the decrease in potential difference. Since the discharge current is composed of such counts, the observed increase in current under irradiation leads to a net increase in the discharge current and the observed decrease in discharge current under radiation leads to a net decrease in the discharge current. Current suppression is maximum when the applied potential is close to the starting potential. This agrees with the maximum negative effect of light at the starting potential reported earlier[15].

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