Positive hysteresis of electrodeless discharge in hydrogen in a co-axial cylindrical configuration

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If the voltage applied to the system increases from a low initial value to a maximum and then reduces progressively to the initial minimum, the variation in rising and falling fields presents three regions of $I-V$ characteristic (i) rising positive approximately linear characteristic up to the breakdown potential of hydrogen gas ($V_b$), (ii) sharply inverting to a negative characteristic over the region $V_b - V_1$ and (iii) a rising characteristic once again for the potential above valley voltage ($V_1$). The region of interest has been the potential range $V_b - V_1$ for which the characteristic is negative. The segments (ii) and (iii) form roughly a parabola. Results show that for increasing and decreasing progress of the applied $V$, the values of unidirectional current are not identical. The values are comparatively less in the increasing progress of the voltage than those in the portion of the positive hysteresis (anti-hysteresis) corresponding to decreasing voltage. These results are discussed and a mechanism for the anti-hysteresis is proposed.

Keywords: Hysteresis, Anti-hysteresis, Discharge current, Electrodeless discharge
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1 Introduction

If a potential is applied to a system of “ozoniser” discharge and is increased from a low initial value to a maximum and then reduced progressively back to the initial minimum, the values of discharge current are not-identical leading to the formation of a hysteresis. This phenomenon was observed while studying on the diminution of the discharge current on irradiating numerous gases with visible light and under varying conditions. However, positive, i.e. anti-hysteresis has also been reported in which the discharge current is larger at a potential while reducing the potential. In order to understand the mechanism for the production of these negative (i.e. regular) and positive (i.e. anti-) hystereses, it is of marked significance to study the effect of potential on the secondary processes which govern the change of discharge current. The experimental set-up for the production of current in low frequency electric discharge has been developed by Pimpale and others. Pimpale et al. studied the $I-V$ characteristic of air with ac potential using a Siemen’s type discharge tube. They observed a linear $I-V$ characteristic below the breakdown potential of air and a non-linear one above the breakdown potential. They contended that the current is affected markedly by the space charge in the central portion of the curve. Earlier results reported by Pimpale showed that at a low pressure of air, the value of discharge counts in dark was greater in rising field than in the falling, conforming to the general physical theory. Similar phenomenon of hysteresis in cosmic ray intensity has recently been reported by Pankaj et al.

Chang et al. investigated the effect of hysteresis in a narrow co-axial wire-pipe discharge tube through which the gas was passed. They found that onset of corona discharge depends upon the temperature of gas. This effect is more or less similar to the results reported, by Pimpale, in Siemen’s type ozonizer activated by low frequency ac corona discharge.

The present work reports the anti-hysteresis effect in hydrogen subjected to electrodeless discharge. The most probable reason for the failure of reproducing the results in this system is also described.

2 Experimental Details

The experimental set up employed to investigate the discharge through hydrogen is shown in Fig. 1. The electrical feeding system has been adopted to feed a “volume ozoniser” with a voltage up to 560 V and at a frequency of 50 Hz. The current has been analysed with a single channel pulse height analyser assembly, using a bias of 5 V. The volume ozoniser is a Siemen’s type discharge tube. The inner and outer radii of the volume ozoniser are 1.2 cm and 1.6 cm, respectively. Its height is 15 cm. Well dried and purified hydrogen gas ($H_2$) at a pressure of 4 Torr is filled in the ozoniser. Electrodes are external in the
form of co-axial cylinders. The inner electrode is set at a high a.c. potential whereas the outer electrode is at zero potential.

3 Results

The application of high tension between the electrodes shows that the glow is generated through all the areas in the gas space during discharge and the glow increases on increasing the potential. The measurement of $I-V$ characteristic displays an anti-hysteresis, i.e. the discharge current is larger at a potential and then increases while reducing the potential (Fig. 2). Initially, the discharge current increases linearly with the applied potential up to the breakdown of the gas. On increasing the potential further up to $V_v$ (valley potential) however, the current decreases. Above $V_v$, the current increases rapidly with the potential. Moreover, the loop area of the hysteresis (i.e. the energy dissipation) is more at a lower bias and decreases faster at higher bias.

A number of researchers studied the time delay phenomena, which generated hysteresis effect between high and low energy cosmic rays. However, the apparently anomalous results (i.e. the anti-hysteresis) in the present case cannot be explained by the general physical theory. On the other hand, the three regions of $I-V$ characteristic corresponding to hydrogen in the present case agree well with the general shape of the $I-V$ characteristic of a tunnel diode. The interpretation of these regions is as follows:

(i) Primary mechanism

It is known that the number of charged particles (electrons) arriving at the high tension (HT), the distributed capacity and other electrical factors attached to the system determine the amplitude of the pulse (bias) used during the measurements. That is, the larger the number of electrons produced in an avalanche created by any secondary process and deposited on the surface of inner glass cylinder (HT), the larger is the bias or the amplitude of a pulse. There are different secondary mechanisms for the liberation of electrons which under fields yield avalanches. The relative significance of these processes, responsible for the maintenance of any discharge, has been well discussed by Khosla and Ramaiah.

As pointed out earlier, the secondary electrons produced in the gas phase especially in the neighbourhood of the low tension (LT) electrode by any process acquire energy under fields and start ionization of gas particles by inelastic collisions roughly from a point away from the LT. The production of electrons takes place exponentially, the number of electrons generated by every secondary electron is given roughly by $\exp (\alpha \, d\, r)$, where $\alpha$ is the coefficient representing the number of ionizing collisions in path of unit length and $d\, r$ the electrode separation. The gas amplified current received at the inner high tension electrode in the non-self sustained region can then be expressed as:

$$I = I_0 \exp \int_{r}^{R_e} \alpha \, d\, r$$  \(\ldots (1)\)

where $I_0$ is the electron emission current from the low tension electrode by external radiation,
\[ \int r \alpha \, dr \] is an exponent.

The value of this exponent can be fixed by the above primary process of ionization and excitation by electron-impact and this value is largely dependent on the type of gas and the geometry of the field. Thus, small changes in an exponent compensate for a large variation in the secondary action. The integral yields the total ionization and represents the number of electrons that arrive from the radius of some of intense ionization \( r \) to the inner (H.T.) electrode (radius = \( R_{\text{in}} \)). The positive ions created in an avalanche remain essentially at rest during the creation of the avalanche, since the velocity of electrons is faster than the velocity of ions. This renders the breakdown potential very active to primary action and not sensitive to secondary action. Further, most of the ionization is 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 stabilize the current as implied by Eq. 2

\[ I = I_0 \exp \left[ (R_{\text{in}} - R) \alpha \right] \quad \ldots (2) \]

According to Eq. (2), the general shape of the curves in the present case corresponds approximately to a linear at least below the breakdown potential of gas. The same holds good according to Werner's equation, modified on the assumption that the radius of the zone of intense ionization surrounding the inner glass cylinder does not change with increasing potential\(^{16} \). Where Werner’s modified equation is\(^{16} \)

\[ (V - V_g)V_g = V_r = I R_1 \quad \ldots (3) \]

where \( R_1 \) has the dimension of a resistance and expresses the corona gap resistance and \( V_r \) is the reduced potential. When \( r = R_{\text{in}} \), radius of outer glass cylinder, \( R_1 \) becomes zero. Under these conditions, theoretically no space charge is active. This condition holds good for the region below \( V_g \).

(ii) Formation of negative space charge

As the applied high tension (HT) voltage is further increased, the current in a system starts decreasing and reaches a minimum at the valley point, for the valley voltage \( V_v \). This negative resistance characteristic has been used either as an amplifier\(^{17} \) or an oscillator\(^{18} \) or a switching device\(^{19,20} \) (gate or flip flop) in computers. The electrons emitted from L.T. cannot cross the cloud of electrons (i.e. the negative space charge) formed in the space between L.T. and H.T. and prevent others from reaching the H.T.

(iii) Neutralization of negative space charge

If the applied \( V \) is raised above \( V_v \), the discharge current shows a rapid and non-linear growth. The electrons, now, gather large velocities and ionize the gas. The positive ions (i.e. positive space charge) neutralize the effect of negative space charge. However, the hydrogen ions are at least 1800 times heavier than electrons. The energy of ions is much smaller than that of electrons due to losses of collision. Thus, the result is that one positive ion is able to neutralize the space charge of hundreds of electrons. This effect is further enhanced by changes that occur in the distribution of potential.

4 Discussion

When the discharge occurs through a gas across two dielectric surfaces (i.e. glass walls), the charge distribution over each of them is not uniform and therefore, each of the surfaces is not equipotential. Each surface is divided into small elementary areas, called sites, which are at different potentials. The discharge takes place between pairs of such sites on the opposite walls due to the wall charge field produced by an applied potential\(^{21,22} \). The electrical stress on hydrogen, \( E_g \), due to the wall charge is given by the equation\(^{22} \)

\[ E_g \cdot \varepsilon_g = E_w \cdot \varepsilon_w \quad \ldots (4) \]

where, \( E_w \) is the stress across the dielectric walls and \( \varepsilon_g \) and \( \varepsilon_w \) are the permittivities of hydrogen and the wall-material, respectively. Normally, \( E_g > E_w \) if the wall material is glass.

On account of two opposite forces (a) the electrical stress in the gaseous medium and (b) the electrical field across the glass walls, the internal glass walls are not held firmly and can be released easily when the potential across the gas phase is greater than its breakdown potential. In the discharge process, the electrons released from the negative wall produce electron avalanches in the gas, which after reaching the opposite wall reduce the positive charge on its surface. Thus, when the potential difference becomes smaller than the starting potential, the discharge is terminated. The subsequent discharge
takes place when the potential is restored. This restoration of the potential occurs as a result of the leakage of the charges through the glass walls or perhaps, also in part, by surface conduction. The finite time interval between the consecutive pulses occurring between a pair of sites on the opposite walls is the leakage time constant or simply a time constant.

It is well known that adsorption of gases on the surfaces of electrode takes place under electrical discharge. In the case of atomic hydrogen, this effect is more prominent because the adsorption is enhanced when the gas is in the atomic state. It is possible to imagine that under heavy discharge during the electro-conditioning, hydrogen is dissociated into its atomic state and is readily adsorbed by glass walls of the discharge tube. Thus, the electrode-surfaces get coated with adsorbed gas layers. This layer has a low work function.

When this adsorption increases, the number of sites (i.e. the charge) on the surfaces of glass walls decreases whereas if the adsorption decreases, the number of sites (i.e. the charge) on the glass-surfaces increases.

The large values of discharge current in dark for descending field (i.e. the anti-hysteresis) means the decrease in the number of sites upon the surface of glass walls and hence the total charge present upon these sites increases, assuming the charge density on glass walls remains unaltered. It also means the decrease in the number of sites while the field increases.

5 Conclusion
The number of sites on the surface of glass walls and the total charge present upon those sites determine the current. The current passes through a co-axial cylindrical all-glass vessel containing H2 at P = 4 torr and activated by a low frequency (50 Hz) potential. The measurement of I-V characteristic displays an anti-hysteresis, i.e. the discharge current is larger at a voltage while decreasing the voltage.

The mechanism of electrodeless discharge may probably be applied as a suppression of electroluminescence in ferroelectric BaTiO3 crystals. Ferrites having a rectangular loop may find useful application in memory cores of computers. The study of hysteresis is extremely useful in the choice of ferromagnetic materials for specific application.

References