

## Alterations in anode sheath behavior in a leaky DC discharge system

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This paper reports the behavior of anode sheath in a planar dc discharge system brought about by changing the plasma boundary. Although no Negative Differential Resistance (NDR) region was observed in the current – voltage ( $I_d$  -  $V_d$ ) characteristics of the discharge in fully open or fully closed cases [1], an NDR region (sudden increase in  $I_d$  along with sudden drop in  $V_d$ ) is observed in *partially open* cases due to the plasma leaking into the stainless steel (SS) chamber. It is shown that there is an ion sheath formed at the anode before the NDR which changes into an electron sheath after the NDR and that the flipping from an ion to electron sheath is an outcome of the large current required to be supplied by the anode.

Another interesting feature observed is that as  $I_d$  and  $V_d$  increase monotonically from their initial values, a sharp kink [a sudden, small increase (drop) in  $I_d$  ( $V_d$ )] can be seen in the discharge characteristics. After the kink there is a small reduction in the slope of the  $I_d$  -  $V_d$  characteristics indicative of an increase in conductance of the circuit. This is also borne out by the difference between the anode and the plasma potentials (through LP measurements).

### 1. Introduction

It is well-known that plasma being quasi-neutral, sustains negligible electric fields within its volume with most of the potential differences (*p.d.*) being dropped across the plasma-boundary wall, also termed as sheath regions. These sheaths may be ion rich, electron rich or may even develop into a double layer depending on the discharge conditions and electrode geometry. In general, ion sheaths are the norm at the cathodes, primarily because of the fact that electron mobility is much larger than ions which results in electrons being lost from the plasma faster than ions. Hence, a potential barrier is created between plasma and boundary to protect further loss of electrons as well as accelerate the ions from plasma to electrode so as to maintain quasi-neutrality in the plasma volume. At the anode, electron sheaths are usually formed due to the positive bias on the electrode *w.r.t.* the plasma potential ( $V_p$ ) which demands electrons to bleed out of the plasma so as to maintain the discharge current ( $I_d$ ). In some cases, so as to prevent the excessive bleeding of the electrons, plasma tends to develop a double layer (back-to-back electron-ion sheath) [2, 3]. The dynamical response of the sheath to different configurations has been under investigation in the recent past [4, 5]. It is observed that by increasing the size of the positively biased electrode, the nature of the sheath may change *i.e.*, a transition of an electron sheath to an ion sheath through an intermediate double layer [4]. Scheiner *et. al.* [5] have observed a transition of ion-to-electron sheath numerically

(using particle-in-cell simulation) near a small electrode, when the electrode bias is changed from below to above  $V_p$ . In this paper we have discussed the development of a strong ion sheath with increasing  $I_d$  and its flipping into an electron sheath after the NDR under the effect of change in plasma-boundary wall.

## 2. Experimental Setup

In this experimental setup, asymmetric parallel electrodes (anode dia. = 38 mm, cathode dia. = 76 mm, separation = 35 mm) were placed inside a glass tube (I.D.  $\approx$  95 mm) and enclosed by mica discs within the glass tube as shown in Fig. 1. The whole assembly was placed in a SS chamber. Both cathode and SS chamber were grounded. A small annular aperture in the mica disc was made on the anode side through which plasma can leak into the outer SS chamber (partially exposed).

The external circuit was completed through a variable DC power supply and a variable ballast resistor,  $R_B$  [not shown in Fig. 1]. The argon gas pressure ( $p$ ) was varied from 800 mTorr to 1400 mTorr. An axially movable Langmuir probe (LP) [as shown in Fig. 1] is used for the estimation of different plasma parameters [electron density ( $n$ ), electron temperature ( $T$ ) and  $V_p$ ]. The details of the LP procedure, data acquisition, its validity, and analysis of the plasma parameters from the  $I$ - $V$  data can be found elsewhere [6]. An indigenously developed LABVIEW based semi-automated XY recorder was used for recording the experimental data.

## 3. Experimental Results and Discussions

### 3.1. Discharge Characteristics

Discharge characteristics are recorded by varying the DC power supply voltage ( $V_{sup}$ ). Fig. 2 depicts the temporal variation of  $V_d$  with  $I_d$  for increasing  $V_{sup}$  upto  $I_d \approx 50$  mA ( $I_d$  limited by  $R_B$ ) and then decreasing up to a minimum  $I_d$  at 1200 mTorr pressure. Initially as  $I_d$  increases linearly up to  $\approx 9$  mA,  $V_d$  also increases but there is a kink [a small increase (drop) in  $I_d$  ( $V_d$ )] at  $V_d \approx 275$  V which correspond to  $I_d \approx 3$  mA [point (b) in Figs. 2 and 3]. At point (c) there is a sudden jump ( $\approx 9$  mA to 16 mA) in  $I_d$  and a sudden drop ( $\approx 310$  V to 225 V) in  $V_d$  [point (c) to (d) in Fig. 2], giving rise to a negative differential resistance (NDR) in the  $I_d$  -  $V_d$  characteristics [point (c) to (d) in Fig. 3]. This NDR is observed as a result of the discharge leaking out into the conducting SS chamber through a small annular aperture between the inner glass wall and the anode side mica disc. When  $I_d$  further increases by increasing  $V_{sup}$ , there is another drop in  $V_d$  at  $I_d \approx 40$  mA [from (e) to (f) in Fig. 3] which implies a second NDR in the  $I_d$  -  $V_d$  characteristics. It may be noted that this NDR is not sudden but controllable and slowly varying. Further decreasing  $I_d$  from its maximum value ( $\approx 50$  mA), a

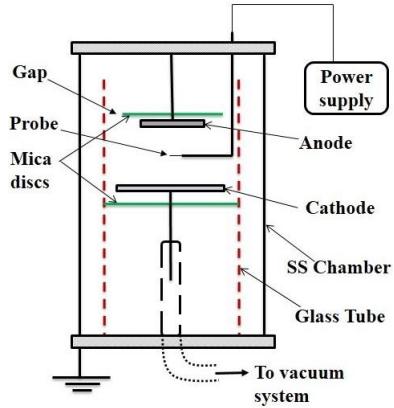


Fig. 1: Schematic diagram of experimental setup.

hysteresis is observed in the discharge characteristics (g→h→j in Figs. 2 & 3). The evolution of plasma parameters at different  $I_d$  (1.5, 2.5 and 5 mA) can provide an insight into the evolution of the discharge characteristics, discussed in the subsequent section.

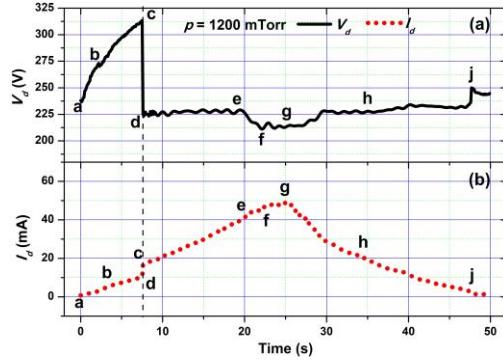


Fig. 2: Variation of  $I_d$  and  $V_d$  with time at  $p = 1200$  mTorr

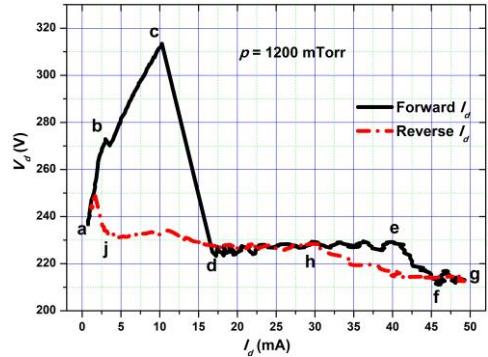


Fig. 3:  $I_d$  -  $V_d$  characteristics at  $p = 1200$  mTorr.

### 3.2. Plasma Profile

Fig. 4 shows the different plasma parameters estimated by LP located at the mid plane ( $z \approx 18$  mm) between the anode and cathode. As  $I_d$  increases up to 7.5 mA (*i.e.* before NDR), the bulk electron density ( $n_e$ ) increases from  $2 \times 10^9$  cm $^{-3}$  to  $8 \times 10^9$  cm $^{-3}$ , warm electron density ( $n_w$ ) increases from  $2 \times 10^6$  cm $^{-3}$  to  $10 \times 10^6$  cm $^{-3}$ ,  $V_p$  increases from  $\approx 240$  V to 325 V with the bulk electron temperature ( $T_e$ ) being almost constant. After the NDR at  $I_d \approx 16$  mA,  $V_d \approx 225$  V [point (d) in Fig. 3]  $V_p$  decreases to  $\approx 220$  V. So there is a drop in  $V_p$  across the NDR from 325 V to 220 V.

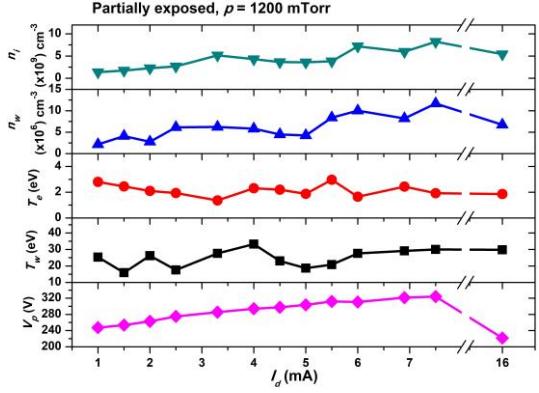


Fig. 4: Plasma profile at different values of  $I_d$  in the mid plane between anode and cathode at  $z=18$  mm.

### 3.3. Plasma Potential and Anode Potential

In the present experimental setup, the cathode is grounded along with the chamber and the anode is biased at a positive potential. This configuration ensures that  $V_p$  is always positive *w.r.t.* ground and hence one always obtains an ion rich sheath at the cathode, resulting in ion acceleration across the cathode sheath for ion induced secondary electron emission. It is well known that in DC discharges these secondary electrons are mostly responsible for the self-sustenance of the discharge. The interesting part is the variation of the *p.d.* between  $V_p$  and anode potential ( $V_A = V_d$  for the present case). Fig. 5 shows the plot of  $V_p$  in reference to  $V_A$  at different values of  $I_d$ . For  $I_d \leq 3$  mA [*i.e.* up to the kink in the discharge characteristics, point (b) in Fig. 3],  $V_p$  is nearly equal to  $V_A$  so  $\Delta V = V_p - V_A$  is negligibly small, indicative of absence of any stable sheath before the kink although it develops into an ion sheath after the kink and remains so right up to the NDR peak point [point (c) in Fig. 3], which can be seen in

Fig. 5 along with a drop of  $\Delta V \approx +10$  V. After NDR, this ion sheath flips into an electron sheath. Figs. 6(a) and 6(b) shows axial plasma profiles at  $I_d \approx 1.5$  mA and 2.5 mA respectively before the kink and Fig. 6(c) shows the same for  $I_d \approx 5$  mA after the kink, which depict the same relative behaviour of  $V_p$  and  $V_A$  as discussed earlier in Fig. 5. As seen in Fig. 6,  $V_p$  ( $z: 9$  mm  $< z < 27$  mm) is  $\approx V_A$  at low  $I_d$  ( $\approx 1.5$  mA) before the kink in  $I_d$  -  $V_d$  curve ( $I_d \approx 3$  mA). As discharge approaches this kink region, one observes  $V_p$  close to the anode evolving into values greater than  $V_A$  whereas closer to the cathode,  $V_p \approx V_A$ , *i.e.*,  $V_p$  ( $z: 6$  mm  $< z < 21$  mm)  $> V_A$  and  $V_p$  ( $z: 21$  mm  $< z < 27$  mm)  $\approx V_A$ . Subsequent to the kink and before NDR ( $3$  mA  $< I_d < 9$  mm),  $V_A$  is lesser than  $V_p$  right up to the plasma-cathode sheath boundary. After NDR plasma profiles are difficult to obtain but as observed from Fig. 5, the anode sheath develops into an electron sheath *i.e.*, an ion to electron sheath flip occurs across the NDR.

#### 4. Summary

In this paper changes in the nature of anode sheath in a parallel plate DC discharge system has been discussed with respect to a leaking boundary. It is observed that an NDR is triggered when plasma leaks out into the outer stainless steel chamber from a small aperture in the surrounding dielectric boundary walls. As  $I_d$  increases, initially an ion sheath is formed at the anode with small drop across anode sheath which develops into a strong ion sheath after a

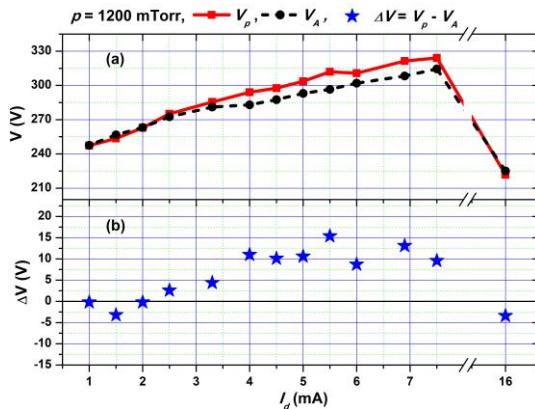


Fig. 5: Plot of plasma potential with respect to anode potential at different  $I_d$ .

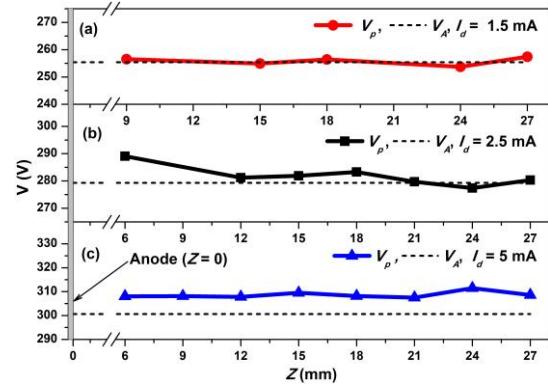


Fig. 6: Axial variation of plasma potential and anode potential at different  $I_d$ .

kink in the discharge characteristics. The ion sheath observed before NDR flips into an electron sheath after the NDR in order to maintain the current requirement at the anode.

#### 5. References

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