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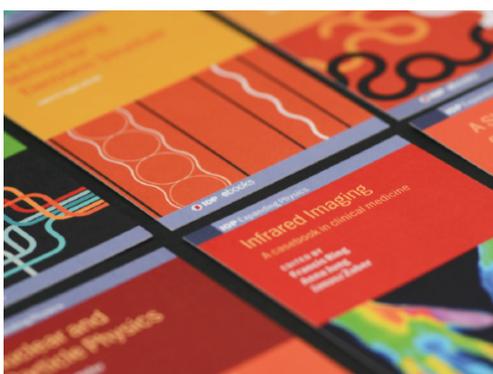
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Magnetized microdischarge plasmas in low pressure argon and helium

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Abstract. Magnetized microdischarge plasmas have been generated in low pressure argon and helium environments with planar electrodes and a non-uniform magnetic field configuration that can cause closed $E \times B$ electron drift. The electrode gap was 1 or 3 mm and the operating gas pressures were 0.5-55 Torr for argon or 1-100 Torr for helium. The breakdown voltage is found to be low with the use of a magnetic field at lower pressures as a result of the effective magnetization of electrons. The current-voltage relation at low pressures departs from the well-known current-voltage scaling that holds in the absence of a magnetic field. The magnetized microdischarge system for argon with copper electrodes exhibits a transition from positive to negative resistance when the operating pressure is decreased to below 10 Torr.

1. Introduction

The development of microdischarges, microplasmas, or micro-ion sources has attracted much interest for a range of applications, such as local etch processing [1], chemical analysis [2], materials synthesis [3,4], surface treatment/modification [5], and sterilization [6]. It has been demonstrated that microdischarges can be ignited and sustained at relatively high pressures, removing the necessity of vacuum chambers in some cases. However, as a trade-off of this, the operation in a highly collisional environment precludes applications that may require high ion energy. At low pressures and low powers, the generation and operation of a microdischarge may develop new fields of applications that benefit from focused, high current density, and highly energetic ions, such as spatially constrained surface treatment or modification, sputtering, low energy ion implantation, and micropropulsion. By using a magnetic field, we have demonstrated microdischarge generation under low pressure environments [7, 8] and its application to the development of a micropropulsion device [9].

In this paper, we present a basic characterization of a direct-current (DC) magnetized microdischarge plasma, which is generated with planar electrodes and a non-uniform magnetic field configuration promoting closed $E \times B$ electron drift in argon and helium environments. Furthermore,

the results of breakdown voltage measurement in a helium environment, in which the breakdown voltages with and without a magnetic field are experimentally compared, are also presented.

2. Experiments

2.1. Breakdown voltage measurements

The electrode and magnetic field configurations used for breakdown voltage measurements are almost the same as those described in Ref. 8 and similar to the schematic diagram given in Fig. 1. The powered electrode, which has a magnetic circuit, is made of aluminum. The grounded is either a thin film of indium tin oxide (ITO) on a transparent plastic sheet (for argon discharges), or simply, an aluminum plate (for helium discharges). The magnetic circuit incorporates a ring-shaped SmCo permanent magnet with a high-purity iron core to form the poles. The inner diameter of the magnet is 4 mm, the outer diameter is 14 mm, and the thickness is 3 mm. The outer diameter of the iron core is 3 mm. The magnetic field, which drives closed $\mathbf{E} \times \mathbf{B}$ electron drift in the presence of a plasma, was obtained from a numerical simulation using a two-dimensional axisymmetric finite element solver [10], and the magnetic field strength near the electrode surface is found to be about 1 Tesla [8]. This field can result in cyclotron motion with a Larmor radius of 10 μm for an electron with energy of 10 eV. The discharge gap was fixed for this experiment at 1 mm. Microdischarges were generated with a DC power supply in argon (Ar) or helium (He). Discharge polarity examined in this study was set to be negative for Ar (so that the cathode housed the magnetic circuit) and varied for He. We also measured the breakdown voltages in the absence of magnetic fields with He.

2.2. Visual observations and current-voltage characteristics

The DC magnetized microdischarge plasmas were visually recorded and the current-voltage (I - V) characteristics were documented for Ar with a discharge configuration shown in Fig. 1. Here both electrodes were made of copper (Cu). The powered electrode was the cathode. The inner diameter of the SmCo magnet was 5 mm, the outer diameter was 17 mm, and the thickness was 5 mm. The outer diameter of the iron core was 4 mm. The discharge gap was fixed at 1 mm, except for the case when a photograph of an annular-shaped microdischarge was taken with a wider electrode gap (Fig. 4 below). The discharge current was evaluated from the measured voltage across a ballast (10 k Ω) resistor located between the power supply and the powered electrode (cathode).

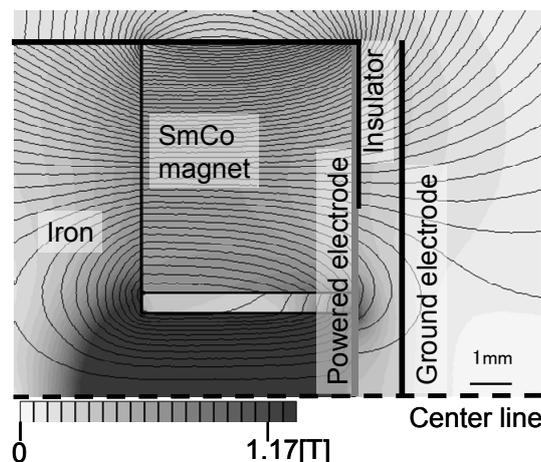


Fig. 1. Schematic of the discharge cross section.

3. Results and Discussion

3.1. Breakdown voltage measurements

The breakdown voltage curves are shown in Fig. 2. Note that in the absence of a magnetic field (i. e., the open squares for He discharges) the breakdown voltage follows the well-known Paschen curve as a function of the operation pressure. For He discharges, it is seen in Fig. 2 that the breakdown voltage has a minimum near 45 mm·Torr, regardless of the presence of a magnetic field and the discharge polarity. This is probably because the initial breakdown in this system at relatively high pressures takes place near the discharge center, where the magnetic field is oriented along the discharge center line (axis), and it is expected that here the motion of the electrons from the cathode to the anode is only weakly affected by the magnetic field. Indeed when the pressure is relatively high a (thin) plasma sheet is been observed to be generated along the center line, in addition to a bright ring of plasma, as shown in Fig. 3.

The breakdown voltage curves with a magnetic field show more interesting features at lower pressures (1-20 Torr in the case of He discharges). When the electrode with the magnetic circuit is powered at negative voltages, the breakdown voltages are found to be significantly lower than those for discharges without magnetic field. In contrast, when the powered electrode is at a positive bias voltage, the curve is slightly lower than that for the discharges without magnetic field. These results indicate the magnetic field strongly influences the electron motion at these low pressures. As shown in Fig. 1, some magnetic field lines that cross the powered electrode (which is in contact with the magnet) and extend toward the grounded electrode return to the powered electrode without crossing the grounded electrode. On the other hand, all magnetic field lines that cross the grounded electrode also pass through the powered electrode or insulator. Therefore, when the powered electrode is positively biased, secondary electrons emitted from the grounded electrode (i.e., cathode) can all reach the powered electrode (or the insulator) without diversion as they are likely to drift along the magnetic field lines at a very low pressure. Conversely, if the powered electrode is negatively biased, some secondary electrons emitted from the powered electrode (i.e., cathode) may be trapped by the bent magnetic field lines and have a higher residence time in the plasma. This increased residence time increases their probabilities of colliding with neutral species, increasing electron collisionality, leading to higher ionization probabilities and therefore lower breakdown voltages.

The results with Ar are qualitatively similar, perhaps more regular and clear at lower pressures, and it appears that in addition to the breakdown voltage minimum near 15 Torr, there exists a second minimum near 1 Torr [8].

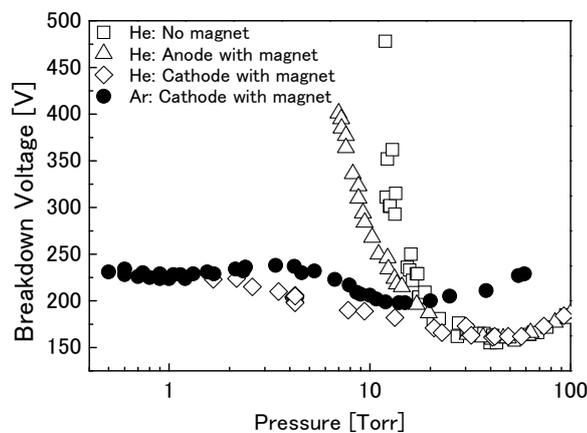


Fig. 2. Breakdown voltages as functions of pressure: Ar and He environments, 1 mm gap.

3.2. Visual observations

Side views of generated DC magnetized microplasmas in 0.5-10 Torr Ar environments are shown in Fig. 3. At these low pressures a clear annular-shaped microdischarge has been generated successfully with strong emission from regions of strong $\mathbf{E} \times \mathbf{B}$ drift. An example of the annular-shaped microdischarge (with a 3 mm electrodes gap) is shown in Fig. 4. In contrast, when operating at higher pressures we have confirmed that, in addition to a more diffuse annular glow, a luminous glow appears along the central axis, where the magnetic field is almost parallel to the electric field, as shown in ref 8. The fact that the images of the plasmas shown in Fig. 3 are all sharper than those for discharges at higher pressures, e. g. 50 Torr, suggests that electrons are better confined by magnetic fields at lower pressures.

The brightness of the annular-shaped microdischarge was observed to increase with decreasing pressure as long as the pressure is higher than 1 Torr, as seen in Fig. 3. We attribute this in part to higher magnetization of electrons that causes higher ionization degrees. This is consistent with the observed higher optical emission ratio of Ar^+ line (488.0 nm) to Ar line (696.5 nm), measured by a CCD spectrometer (Ocean Optics model HR4000). At 0.5 Torr, on the other hand, the optical emission strength and the ratio of the emission lines are lower than those at 1 Torr, the reason for which is not yet clear.

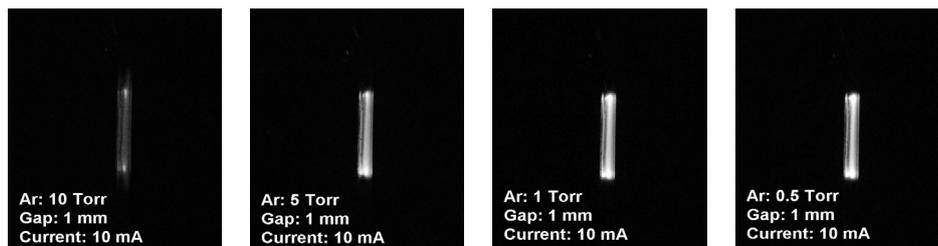


Fig. 3. Side views of magnetized microdischarge plasmas; Ar, 1 mm gap. The cathode with the magnetic circuit is on the left side.

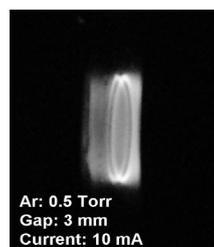


Fig. 4. An oblique view ($\sim 10^\circ$ from the electrode surface) of a magnetized microdischarge plasma: Ar 0.5 Torr, 3mm gap. The cathode with the magnetic circuit is on the left side. Note that the left-side ring is an image of the right-side ring reflected on the electrode surface.

3.3. Current-voltage characteristics

Figure 5 shows the current-voltage (I - V) characteristics of Ar microdischarges. The anode and cathode material is copper and the electrode gap is 1 mm. It is clearly seen that the I - V relation changes significantly at different pressures between 5 Torr and 10 Torr. Although a quantitative measurement of the discharge current density has yet to be made, at 5 Torr the current density may not be smaller (for the same total current) than that at 10 Torr because the plasma area in contact with the electrode seems to be smaller at 5 Torr.

It is seen in Fig. 5 that, at lower pressures (0.5 ~ 5 Torr), the I - V characteristics show negative resistance, i.e., a lower voltage operation results in a higher current density when the total current is maintained at ~ 3 mA or larger. At a high pressure, i.e., 10 Torr, on the other hand, the I - V

characteristics show positive resistance. We note that, at lower pressures, the I - V characteristics is also different from the well-known I - V characteristics Jn^{-2} (here, J is the current density and n is the neutral particle density) scaling in the absence of a magnetic field [11].

A concentration of copper (Cu) emitted from the electrodes in the discharge may in part account for the transition from positive to negative resistance in the I - V curves as the operating pressure decreases. Cu atoms are known to be easily sputtered from a Cu surface. Furthermore, sputtered Cu in the gas phase may be highly ionized by high density electrons maintained by magnetization. Therefore, Cu density in the plasma may be high enough to affect the plasma conductivity, which in turn affects the I - V curve. Indeed we have confirmed that the ratio of the optical emission strengths of Cu (521.8 nm) to Ar (763.5 nm) increases as the total current increases (in the range of 3-10 mA) and the pressure decreases (0.5-10 Torr).

This argument is also indirectly supported by our recent study of a similar discharge with a carbon (C) cathode (which have much lower sputtering yields) and an ITO anode, where it has been shown that the I - V curve with 150 mTorr has a positive slope. The electrode gap was 2 mm. It is also observed that this I - V curve departs from the usual Jn^{-2} scaling.

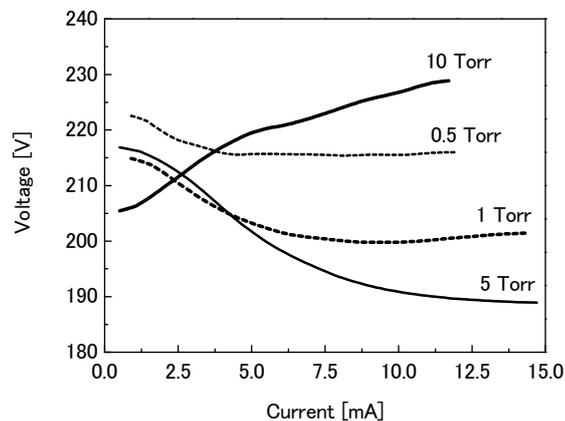


Fig. 5. Current-voltage characteristics: Ar environment, 1mm gap.

4. Conclusions

We have generated magnetized annular microdischarge plasmas in low pressure Ar and He environments with planar electrodes and a non-uniform magnetic field configuration that drives closed $\mathbf{E} \times \mathbf{B}$ electron drift. The breakdown voltage measurements indicate that the electrons are efficiently magnetized and trapped by the magnetic field at low pressures. The suppression of breakdown voltages and their dependence on discharge polarity have been related to the electron trapping by the magnetic field. Strong dependence of the current-voltage relation for Ar discharges on gas pressure has been observed below 10 Torr. Although we have not measured the discharge current density, the scaling of the I - V characteristics at a low pressure departs from that in the absence of a magnetic field. The transition from positive to negative resistance has been observed as the operating pressure decreases from 10 Torr to lower pressures. A higher concentration of sputtered Cu, which results from high ionization rates caused by high-density electrons maintained by strong magnetization, seems to increase the discharge conductivity. Small discharges discussed here, which can be operated stably at low pressures, may serve as useful processing tools, e.g., small energetic ion sources for sputtering or localized surface modification.

The subject of our future research on magnetized microplasmas includes measurements of local ion current densities and cathode sputter rates, characterization of the plasma density, and studies of

effects of nanosecond high-voltage pulses on basic plasma characteristics such as the plasma density and ion/electron temperatures. Figure 6 shows a representative image of a pulsed magnetized microplasma generated in our preliminary study, in Ar at low pressure (in the range of 0.5 Torr ~ 10 Torr, 30 ns pulse width and a 2 kV peak voltage).

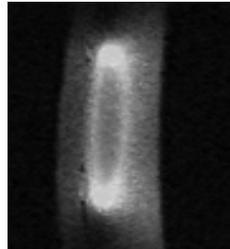


Fig. 6. Photograph of a pulsed magnetized microdischarge plasma; Ar 1 Torr, 3 mm gap, Cu cathode, Cu anode. The cathode with the magnetic circuit is on the left side.

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