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RF BREAKDOWN IN ARGON AT LOW-PRESSURES: EXPERIMENT AND MODELLING

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Abstract. We present results for RF breakdown in argon discharge at low pressures, obtained experimentally and using Monte Carlo code for a frequency of 13.56 MHz. Experimental measurements are conducted at an interelectrode distance (d) of 0.7 cm for pressures (p) ranging from 0.9 to 29 Torr. In our experiment, we employ a technique that eliminates issues related to displacement current. This technique is based on the use of a balanced capacitive bridge, enabling precise breakdown detection and time–domain tracking.

1. INTRODUCTION

Low-temperature plasmas generated using RF power in the frequency range of 1 to 100 MHz find widespread applications in various industrial processes. These applications, such as plasma etching and deposition in the integrated circuit industry, electric propulsion in aerospace, materials processing, surface cleaning, and thin-film deposition, are closely tied to the breakdown itself and the underlying processes. However, when it comes to the breakdown in RF fields, there have been limited attempts to correlate experimentally measured parameters with elementary processes, as is commonly done in the case of direct current (DC) breakdown and discharge. Despite attracting considerable attention from researchers in the past period, the study of RF breakdown faces challenges due to the need to isolate minute breakdown currents from the displacement current. In this study, we present results from RF breakdown measurements at 13.56 MHz in argon and compare them with results from the Monte Carlo simulation, aiming to provide insights that can enhance the efficiency and reliability of these industrial processes.

2. EXPERIMENTAL SET-UP

Breakdown is achieved between two plane-parallel copper electrodes placed inside a tightly fitting borosilicate glass cylinder. This arrangement prevents long-path electric discharges towards the metal parts of the housing while allowing the recording of the emission intensity distribution along the axis of the chamber. The electrodes' diameter is 3.5 cm, and their gap is adjustable. For this work, it was set at 0.7 cm. One electrode is excited, while the other remains at zero potential. The discharge chamber is housed in a special metal box to eliminate interference with the extremely sensitive balance of the capacitive bridge. The box has only openings for recording the emission distribution using an ICCD camera (Figure 1a). The chamber is first evacuated to low pressure ($<10^{-6}$ Torr), and argon is introduced into the system and kept at a slow flow rate to maintain the required gas purity during measurements. Electrodes were treated and stabilized using an argon discharge at 1 Torr for approximately 60 minutes. The treatment is done at a pressure corresponding to conditions in the left-hand branch of the breakdown curve, where ions receive enough energy from the electric field to reach electrodes and remove impurities and oxides from electrode surfaces through bombardment. Throughout the electrode treatment, we monitored changes in the discharge voltage. The process is terminated when further treatment no longer results in a change in the discharge voltage.

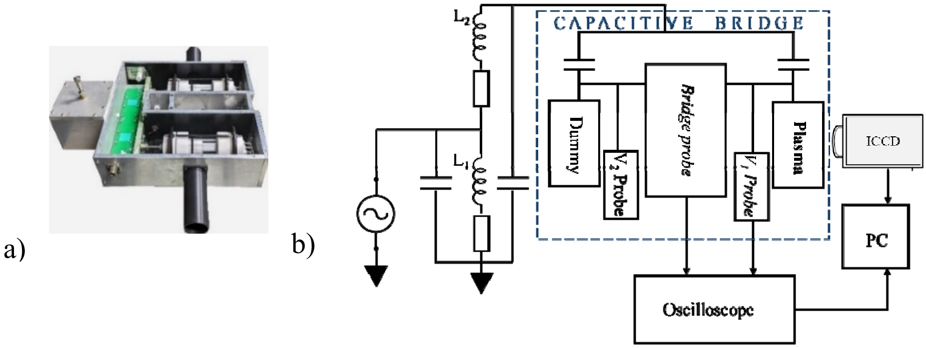

Figure 1: a) Photo of the capacitive bridge, b) schematic of the experimental set-up.

The schematic of the experimental set-up is shown in Figure 1b. The entire electrical circuit is housed in an aluminum box to protect against interference and losses. We utilized a Rigol DG5102 RF signal generator for the power source, which provides a sine signal set to a frequency of 13.56 MHz. This signal is then amplified by a linear amplifier, specifically the Barthel RFA-0.1/50-100 BOO. Coils L_1 and L_2 are part of an inductive coupling and represent a resonant transformer that operates exclusively at 13.56 MHz. This resonant transformer raises the generator voltage to the kilovolt range. The capacitive bridge comprises four capacitors, two of which are physically identical discharge chambers. While the 'Dummy' remains inactive and functions solely as a capacitor, the 'Plasma' acts as the active chamber where the discharge is observed. We monitor the voltage signal from the bridge diagonal using the 'Bridge probe'. Before taking measurements, we calibrated probe V_1, which we use to measure the voltage on the discharge chamber. When the bridge is in balance, the signal from the diagonal is minimal. We detect the moment of breakdown in the gas using an oscilloscope (Keysight Infiniium DSO9104A). The amplitude of the voltage signal from the diagonal of the bridge increases sharply. In other words, the bridge suddenly goes out of balance due to a change in impedance when the breakdown occurs.

3. RESULTS AND DISCUSSION

Figure 2 compares radio frequency (RF) breakdown curves for argon discharge obtained at 13.56 MHz. The curves are derived from measurements (represented by full circles) and Monte Carlo simulations (represented by open circles). The breakdown curve, obtained at the electrode distance of 0.7 cm, covers a range from 0.65 Torr cm to 20 Torr cm. Monte Carlo (MC) code was described and explained elsewhere (Raspopović et al., 1999). These simulations were carried out with only electrons, and their movement is determined by the external electric field (Puač, et al., 2018). The set of cross-sections consists of momentum transfer, two excitations and an ionization cross-section and has been tested for argon swarms in our group (Petrović et al., 2007). Physical processes on the electrodes and the effects of the heavy particles were modelled by factors of reflection $R = 0.4$ and $\gamma = 0.07$. These values were chosen to modify the breakdown voltage curve to better correspond to the measured curve. Breakdown points were determined in two ways. For the right-hand branch, pressure was fixed, and voltage was slowly increased until the number of electrons in time didn't get a positive slope (Savić et al., 2011). Similarly, points in the left-hand branch were determined by fixing the voltage and increasing the pressure until the breakdown occurred. The RF breakdown curves are expected to have the characteristic 'S' shape. However, for small interelectrode distances the curves are distorted (Lisovskiy, Yegorenkov, 1998), in such a way that the left-hand branch is somewhat flattened, which is also observed in both of our curves (experiment and MC).

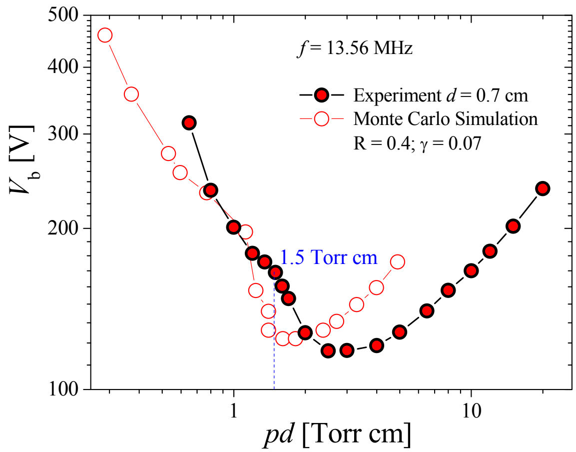

Figure 2: RF breakdown curves for Ar discharge at f = 13.56 MHz. Comparison of experimental results for electrode gap of 0.7 cm (full circles) and MC simulation (open circles) when the secondary electron yield is $\gamma = 0.07$, and the reflection is assumed to be $R = 0.4$.

Analyzing the breakdown behavior at high *pd* values, we observe that the breakdown voltage decreases with decreasing pressure (*p*) (the electrode gap (*d*) is fixed). At *pd*+ = 2.5 Torr cm, the minimum breakdown voltage occurs. Beyond this point, the breakdown voltage increases as pressure decreases further. In the left-hand branch of the curve, an inflexion point appears at 1.5 Torr cm. This inflexion can be attributed to conditions where the amplitude of electron oscillations in the RF field becomes comparable to the interelectrode distance (*d*), leading to increased losses. From this point on, the breakdown is conditioned by a balance between losses at the surface of electrodes and the gain of energy from the increasing field and numerous electrons crossing the threshold for ionization. Thus, the secondary electron yield at the electrodes becomes significant.

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