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Low-pressure gas breakdown in dual-frequency RF electric fields in nitrogen

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Abstract – This paper reports the recorded breakdown curves for dual-frequency (27.12 MHz/2 MHz and 13.56 MHz/50 Hz) discharges in nitrogen. Applying the LF voltage shifts the RF breakdown curve to the region of higher voltages and gas pressures, which is associated with the increased loss of charged particles due to the drift in the LF field. At higher LF voltage amplitudes the LF field contributes to gas ionization, the breakdown voltage for the RF discharge decreases and approaches zero when a self-sustained discharge in the LF field ignites. Applying the RF voltage leads to the decrease in the breakdown LF voltage, possibly due to the decrease of electron losses because of the oscillations in the RF field.

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Recently dual-frequency discharges have found broad application in technological processes of etching SiO₂ [1–4], Si and Si₃N₄ [3], depositing SiO₂, Si₃N₄ [5,6]. In a conventional RF capacitive discharge burning at a fixed frequency f in a discharge chamber with a gap L between the electrodes, at a fixed gas pressure p and a certain value of RF power, the flow of ions to the electrodes and ion energy remain fixed. It is impossible to control these two quantities in a conventional single-frequency RF discharge separately. The problem of separately controlling the ion flow to the electrodes and ion energy is easily solved in the RF dual-frequency discharges, as the high-frequency electric field provides dense plasma while the low-frequency one increases the voltage drop across the near-electrode sheath, and as a result, accelerates ions to higher energy.

Therefore an increased interest to studying processes in dual-frequency discharges is observed [7–16]. At the same time, the gas breakdown in dual-frequency RF discharge remains almost unknown. Whereas the gas breakdown in a single-frequency RF discharge is studied in much detail [17–19], the ignition of a dual-frequency RF discharge still remains to be unexplored.

This paper studies experimentally the ignition of a dual-frequency (27.12 MHz/2 MHz and 13.56 MHz/50 Hz) discharge in nitrogen. The application of a LF voltage (2 MHz or 50 Hz) is shown to increase the RF breakdown voltage, the RF breakdown curve being also shifted to the region of higher gas pressure. At high LF voltage values close to the breakdown potential of the LF discharge, the RF breakdown voltage decreases to zero. Breakdown curves of the 13.56 MHz/50 Hz dual-frequency discharge are similar to the breakdown curves of the RF/DC combined discharge qualitatively, however considerable quantitative deviations in the RF breakdown voltage values are observed.

Experiments were performed in two different set-ups. At the first set-up the RF discharge was ignited in nitrogen over the pressure range $p \approx 0.03$ –6 Torr. RF voltages with the frequencies of 27.12 MHz (RF) and 2 MHz (LF) were fed to the same powered electrode whereas the other one was grounded. The inter-electrode gap was 20.4 mm. The electrodes (143 mm in diameter) were located inside a fused silica tube with an inner diameter of 145 mm. The gas was supplied through small orifices in the powered electrode and then pumped out via the gap between the second electrode and the wall of the fused silica tube.

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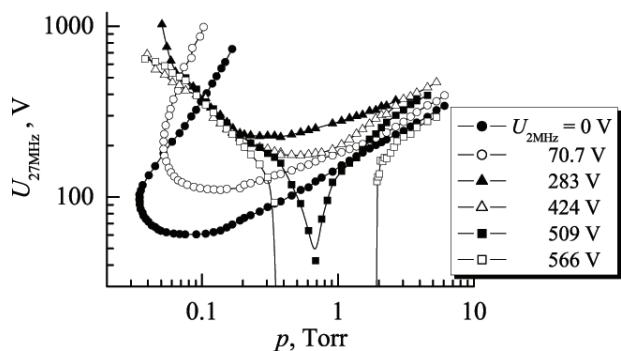


Fig. 1: RF breakdown curves for 27.12 MHz at various fixed values of the LF voltage with the frequency of 2 MHz.

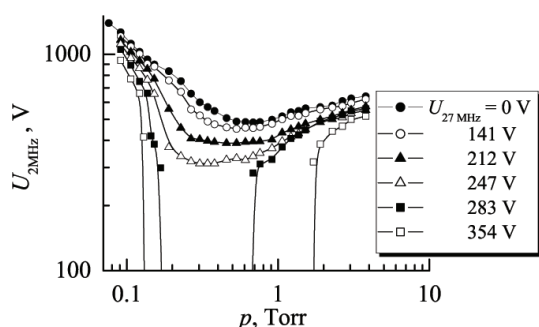


Fig. 2: LF breakdown curves for 2 MHz at various fixed values of the RF voltage with the frequency of 27.12 MHz.

The gas pressure was monitored with 10 and 1000 Torr capacitive manometers (MKS Instruments). The gas flow was fixed with a mass flow controller to 5 sccm, and the pressure regulated by throttling the outlet to the pump. The RF voltage was measured with an RF current-voltage probe (Advanced Energy Z'SCAN).

In another research set-up the RF discharge was sustained between two parallel-plate stainless-steel electrodes of 10 cm in diameter and a discharge gap of 3 cm width. RF voltage with the frequency 13.56 MHz (RF) and LF voltage with the frequency 50 Hz (LF) were fed to the same powered electrode whereas the other one was grounded. The gas delivery and exhaust were accomplished through groups of small holes in one of the electrodes.

Figure 1 shows the RF breakdown curves for 27 MHz (RF breakdown voltage with the frequency of 27 MHz against gas pressure with fixed values of the LF voltage with the frequency of 2 MHz). And fig. 2 shows the LF breakdown curves for 2 MHz (LF breakdown voltage with the frequency of 2 MHz against gas pressure with fixed values of the RF voltage with the frequency of 27 MHz). In general an RF breakdown curve may possess the multi-factor, Paschen and diffusion-drift branches [17]. The RF breakdown curve for $U_{2\text{MHz}} = 0$ within the total pressure range we studied consists of a single diffusion-drift branch (fig. 1). The LF breakdown curve for $U_{27\text{MHz}} = 0$ possesses

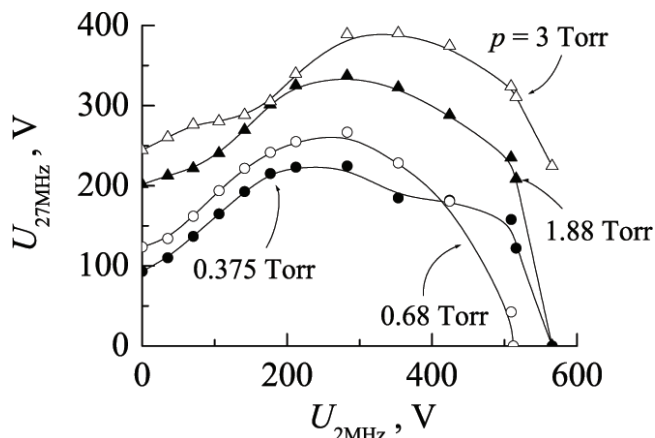


Fig. 3: RF breakdown voltage for 27.12 MHz against the LF voltage with the frequency of 2 MHz at various fixed values of nitrogen pressure.

only the Paschen branch (fig. 2), whereas the diffusion-drift branch may be observed only at higher gas pressure. Applying the LF voltage with the frequency of 2 MHz $U_{2\text{MHz}} < 300$ V shifts the RF breakdown curve for 27 MHz to the region of higher voltages and gas pressures (see figs. 1 and 3). It may be associated with the increased loss of electrons due to the drift in the LF field. At the same time, the section of the multi-valued dependence of the RF breakdown voltage with the frequency 27 MHz against gas pressure, observed at low pressure values, narrows and at $U_{2\text{MHz}} > 250$ V disappears, yielding RF breakdown curves possessing the U-like shape. At higher $U_{2\text{MHz}}$ amplitudes the LF field contributes to gas ionization via electron impact. Besides, positive ions oscillating in the enhanced LF field can collide with the electrode surface and produce secondary electrons. At $430 \text{ V} < U_{2\text{MHz}} < 510 \text{ V}$ a sharp minimum appears in RF breakdown curves for 27 MHz at the pressure value of $p \approx 0.7$ Torr. The minimum in the LF breakdown curve for 2 MHz appears at the same pressure value (see curve for $U_{27\text{MHz}} = 0$). The RF breakdown voltage for $U_{2\text{MHz}} > 300$ V decreases and approaches zero when a self-sustained LF discharge ignites.

Applying the RF voltage with the 27 MHz frequency leads to the decrease in the LF breakdown voltage $U_{2\text{MHz}}$ (see figs. 2 and 4). This may be caused by the decrease of electron losses because of the oscillations in the RF electric field. Besides, the RF field makes a contribution to the ionization of gas molecules. Increasing the RF voltage leads to the shift of the LF breakdown curves to the region of lower gas pressure and LF voltage.

On recording the RF breakdown curves we first fixed gas pressure and applied a chosen LF voltage, and then increased the RF voltage up to the moment of gas breakdown. However, for studying the effect of the RF voltage on the LF breakdown curves we first applied the LF voltage $U_{2\text{MHz}} \approx 200$ V, then we fed the chosen value of the RF voltage and, only after that, increased the LF voltage up to the moment of gas breakdown. If

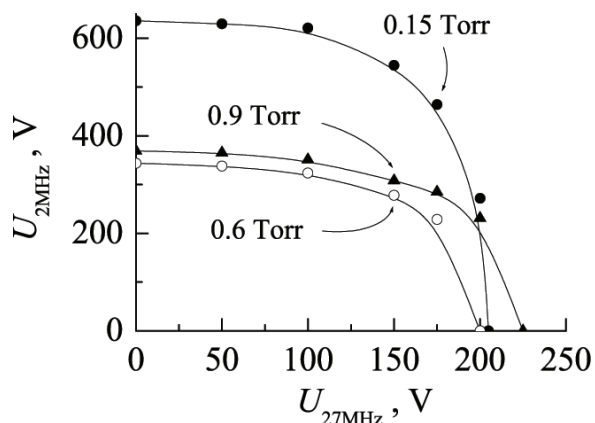


Fig. 4: LF breakdown voltage for 2 MHz against the RF voltage with the frequency of 27.12 MHz at various fixed values of nitrogen pressure.

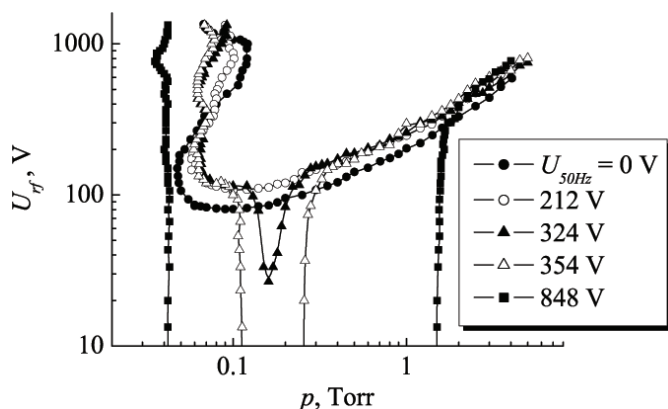


Fig. 5: RF breakdown curves for 13.56 MHz at various fixed values of the LF voltage with the frequency of 50 Hz.

the LF voltage is not applied first, but the RF voltage is fed at once, then we obtain the ignition of the RF discharge at rather low RF voltages. For example, at $p = 1$ Torr for igniting the RF discharge the application of $U_{27\text{MHz}} = 154$ V is required. At the same time, it is clear from fig. 2, that such low RF voltage almost does not affect the ignition of the LF discharge. Therefore we first prevented the ignition of the self-sustained RF discharge via applying the LF voltage, and only then applied the RF voltage, to be able to study the effect of high RF voltages on the LF breakdown.

Now consider our results for dual-frequency 13.56 MHz/50 Hz discharges, obtained in the second set-up. Applying the LF voltage of 50 Hz $U_{50\text{Hz}}$ first shifts the RF breakdown curve for 13.56 MHz to the region of higher gas pressure and RF voltage (see fig. 5). On increasing the LF voltage further, two features are observed in the RF breakdown curve. When the LF voltage applied is close to the minimum breakdown voltage of the LF discharge, a sharply expressed minimum is observed in the RF breakdown curve. At higher LF voltages a self-sustained LF discharge is ignited, therefore

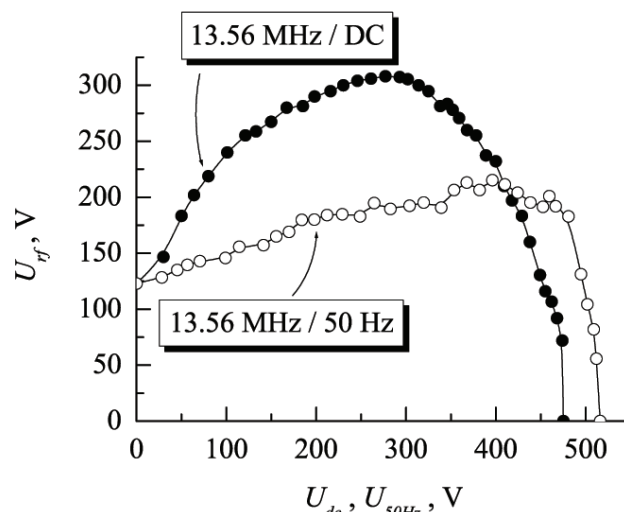


Fig. 6: RF breakdown voltage for 13.56 MHz against the DC and LF voltage with the frequency of 50 Hz at nitrogen pressure 0.5 Torr.

the RF breakdown voltage equals zero (see fig. 6). At LF voltages $U_{50\text{Hz}} > 200$ V an additional region of multi-valued dependence of the RF breakdown voltage against pressure is observed. With the LF voltage increasing, this multi-valued region is shifted to higher values of RF voltage and lower values of gas pressure. Such a multi-valued region was observed earlier in the breakdown curves of the longitudinal combined (RF/DC) discharge [20]. The paper [20] performed a detailed analysis of the observed phenomenon, so we will not pay attention to it here.

Despite the qualitative similarity between the shape of the RF breakdown curves obtained with application of 50 Hz and DC voltages, the RF breakdown voltage values exhibit remarkable quantitative difference. Figure 6 shows RF voltages required for the ignition of the combined (13.56 MHz/DC) and dual-frequency (13.56 MHz/50 Hz) discharges we registered with the nitrogen pressure fixed. Both curves possess a growing section which after attaining a maximum exhibits a decrease of the RF breakdown voltage. However, the application of the 50 Hz voltage involves a much less increase of the RF breakdown voltage than the application of the DC voltage. It may be attributed to uniformly increasing loss of charged particles due to the drift in the DC field associated with the application of the DC voltage. The LF voltage is of a sinusoidal shape with a period $T_{50\text{Hz}} \gg T_{13\text{MHz}}$. Perhaps the dual-frequency (13.56 MHz/50 Hz) discharge is ignited during the time period when the instantaneous LF voltage is small. Here the loss of charged particles due to the drift in the LF field is smaller, and therefore the ignition of the dual-frequency discharge occurs at smaller RF voltages than the ignition of the combined 13.56 MHz/DC discharge.

Thus, this paper presents the breakdown curves of the dual-frequency discharges (27.12 MHz/2 MHz and 13.56 MHz/50 Hz) we recorded in nitrogen. The effects

of the LF voltage on the RF breakdown curves, as well as the effects of the RF voltage on the LF breakdown curves were studied. At small LF voltages applied to the RF discharge to be ignited, the loss of charged particles to the electrodes increases, thus increasing the RF breakdown voltage. At large LF voltages contributing to the ionization of gas molecules via electron impact, the RF breakdown voltage approaches a maximum and then decreases down to zero. Application of the RF voltage always makes the LF discharge ignition easier.

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