Influence of grounded electrode area on breakdown current in RF capcitively coupled plasma

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Abstract

The influence of the grounded electrode area on the ignition voltage in capcitively coupled radio frequency discharge at 13.56 MHz in argon gas is studied experimentally. The results indicate a systematic decrease of the breakdown voltage with increasing grounded electrode area for the same pd value. Results show that the secondary ionization coefficient γ increases with the increase of grounded electrode area. Furthermore, results also the discharge current at the breakdown voltage increases almost linearly with the increase of electrode area suggesting an almost constant current density.

Key words

Plasma,
argon,
rf-discharge,
Breakdown.

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تأثير مساحة القطب المؤرض على تيار الانهيار في البلازما الراديوية ذات الازدواج السعوي

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الخلاصة

تمت دراسة تأثير مساحة القطب المؤرض على فولتية القدح في التفريغ الراديوي السعوي بالتردد 13.56 MHz في غاز الاركون تجريبيا. تشير النتائج إلى الانخفاض النظامي لفولتية الانهيار مع زيادة مساحة القطب المؤرض لنفس القيم للضرب العددي لضغط الغاز والمسافة الفاصلة بين الأقطاب pd. بينت هذه الدراسة أيضا أن معامل التأين الثانوي γ يزداد مع زيادة مساحة القطب المؤرض .إضافة لذلك تبين إن قيمة تيار التفريغ عند فولتية الانهيار الكهربائي يزداد بشكل يكاد يكون خطيا مع زيادة مساحة سطح القطب المؤرض مما يدل على وجود كثافة تيار ثابتة.

Introduction

Radio-frequency discharge receiving increased scientific interest. This is partly due to its widely-spread use in the technology of etching and deposition devices in semiconductor industry [1].

The capcitively coupled radio frequency discharge (ccp), usually involves relatively simple geometry. Two configurations of this geometry are in common use. These are the symmetric discharge, where the plasma is produced between two identical electrodes. The second is the asymmetric discharge system where the plasma formed between two electrodes of different areas [2]. In both cases, Paschen law has been used to describe the breakdown voltage for gaseous ionization between two electrodes. Mathematical model denotes that when the inter-electrode distance less than 15μm the field electron emission play important role in this regime, the transition between Townsend and field emission effects called modified-Paschen curve's [3]. Minimum sparking potential studies using different electrodes materials have shown that the lower work functions give lower sparking potentials [4-6]. Jacobs and LaRocque [7] performed study using a different surface cathode material in dc discharge and they found that the cathode material plays a main role in the breakdown in different inert gases. Ledernez et al [8] used mathematical and experimental arguments to point out that Paschen law must contain the inter-electrode distance as a separation parameter. Lisovskii and Yakovin [9] suggested a modified Paschen law as a function for pressure product the electrode separation pd, and the electrode separation divided by the radii of the electrode or the volume of the discharge. In summary, electrode spacing and electrode diameter have been shown to play important roles not only in governing the RF breakdown voltage but also the shape of the pd breakdown voltage relation and its deviation from the simple conventional dc Paschen curve form [10,11]. However, the basic assumption that the ignition of the discharge depend on the pd and the material of the cathode (electrode) and that the breakdown occurs by the transition from Townsend (pre-ionization) by the few seed electrons, is well established. These electrons are the main players in the sudden increase of the number of electrons by multiplication process to create the avalanche slow electrons which are accelerated by the external applied electric field and start the secondary mechanism by the bombardment cathode by the ions to create the breakdown in the gas. Furthermore, it is well known that electron density of the electrode (cathode) material plays key role in the mechanism of the breakdown in gas [12]. Measurements carried out for the variation of the secondary ionization coefficient for different inert gases with reduced field value [13]. It is our purpose here to present experimental results related to 13.56 MHz RF Argon breakdown voltage as related to pd values and grounded electrode surface area. In this study we concentrate on the variation of breakdown current I_b at the minimum breakdown voltage when using a different grounded electrode surface area.

Experimental Setup

The experimental setup is shown in Fig.(1). It involves a 20 cm in height and 15 cm inner diameter bell jar shaped glass discharge chamber with a Teflon flat base. Two circular flat well polished aluminum electrodes are installed inside the chamber. The upper electrode is 12 cm in diameter with thickness equal 1 cm and fixed at the top. The lower electrode is changeable. A set of electrodes are prepared with diameters of 3, 4, 6, 8, 9, 12 cm in diameters with thickness equal 1 cm are used as lower electrode. The diameter ratio between powered electrode to grounded electrode given by 4:1, 3:1, 2:1, 3:2, 4:3 and 1:1 respectively. A screw mechanism is used to change the distance between the upper and lower electrode in each case. Electrode separations used are 2.5, 3, 3.5, 4, and 4.5 cm with measured error closed to ($\mp$1 mm), the ruler used with centimeter scales each division one millimeter. Both electrodes are Teflon insulated on the side not facing the discharge. The rims of the electrodes are also insulated (This was achieved by machining a solid Teflon disk in away such that the aluminum electrode fits into the machined region). The chamber is connected to the vacuum pump, the gas valve, and the vacuum gauge via three piping connections from the base side. The breakdown voltage is measured for each lower electrode diameter and electrode separation at four pressure values of 10, 15, 25, and 30 Pa measured by (Thermovac Transmitter LEY BOLD VAKUUM company model CAT.No.TTR91S with digital screen gives the value of the pressure in Pascal unit LEY BOLD VAKUUM company CAT.No.378514). The discharge is created using a 13.56 MHz RF generator (AMN 600 R Coaxial Power System) connected via an automatic impedance matching network. The discharge current is sampled using a Rogowski coil. Signal from the cable is applied to the oscilloscope (HAMEG Oscilloscope HM 1004-3 100 MHz HAMEG Instruments Auto set / Recall, Readout/ Cursor, Two Channel), where Rogowski coil-oscilloscope system was calibrated. For each of the above conditions, the RF power is increased slowly until the oscilloscope registers a discharge current signal. This is usually further confirmed by the visual appearance of glow discharge in the chamber. The process is repeated several times to obtain the average ignition voltage in each case with accuracy of about ∓ 3 volts. A digital picture of the current waveform on the oscilloscope screen is recorded in each case.

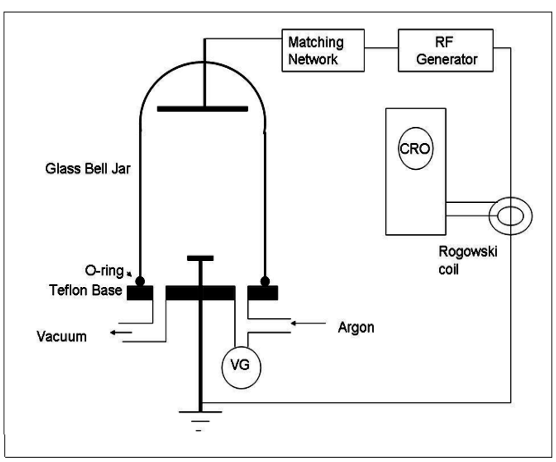

Fig. (1) Experimental Setup

Results and Discussion

Plots of the breakdown voltage against pd values for different grounded electrode surface areas are shown in Fig. (2). It is first of all clear that the breakdown voltages for all pd values suffer a systematic increase with decreasing electrode area (diameter). This means that for the same pd value, a smaller electrode area will need larger voltage to produce the breakdown in the gas. The Paschen minimum breakdown voltage is clear in all plots. The position of this minimum breakdown voltage does not seem to change with electrode area (diameter). However, there seems to be a systematic decrease in the value of the minimum breakdown voltage with increasing electrode area.

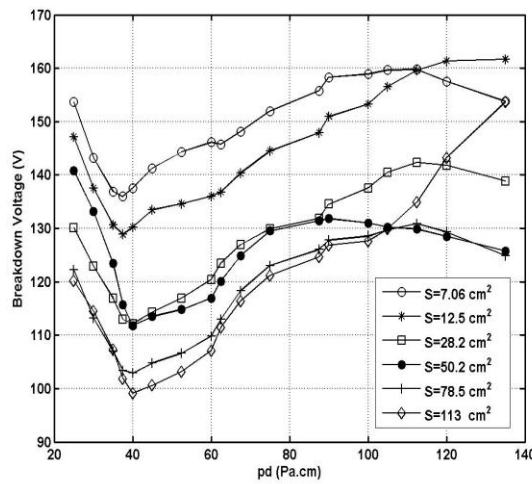

Fig. (2) Plots of breakdown voltage against pd values for different grounded electrode area.

The data to the right side of this minimum is somewhat different from that of a typical well known dc Paschen' curve described by the equation [14] .

$$V_{bk} = \frac{A(pd)}{\ln(Bpd) + C} \qquad (1)$$

where A,B and C are constants, relate to the gas and electrode materials.

In order to describe the experimental data empirically, one can attempt a modified form of Paschen law. It is found that the experimental data can be reasonably described by adding a second order correction term to equation (1). This gives

$$V_{bk} = \frac{A(pd)}{\ln(Bpd)+C} + \zeta\left(\frac{A(pd)}{\ln(Bpd)+C}\right)^2 \quad (2)$$

(2)

By using the fitting for all the Paschen curves in Fig. (2) by the new empirical equation (2) as in Fig (3) shows the fitting for Paschen curves with six grounded electrodes area.

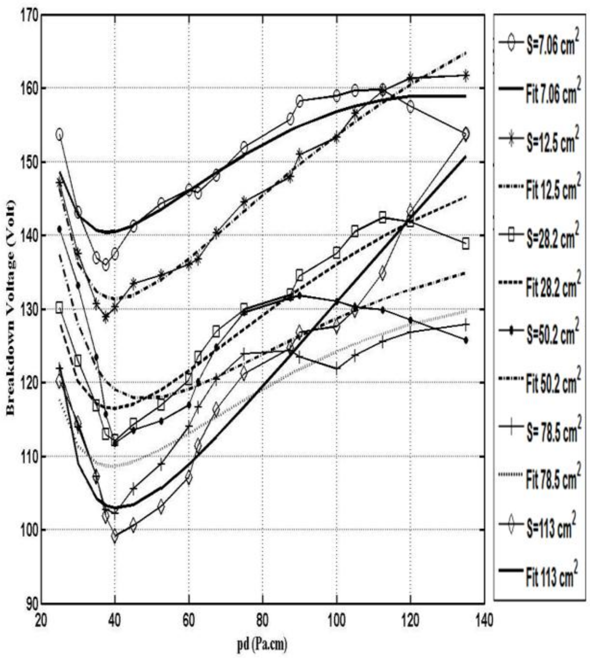

Fig. (3)Typical results of fits to equation (2) for six area values

The aim of establishing the best fitted values of A, B, C and ξ for all the cases in the Fig. (2). If the fitting procedure is to be self consistent, the fitted value of the additional modification constant ξ, should have as small as possible negative value. The results of fits to equation (2) are shown as solid and dashed lines in Fig.(3).

Table (1) Values of fitted parameters in equation (2) for all electrodes

Grounded electrode surface area S cm^2	A	B	C	ξ
7.06	5.5156	0.0878	0.2031	-0.0016
12.5	4.3445	0.0858	0.2416	-0.0014
28.2	3.9631	0.0862	0.2291	-0.0016
50.2	3.5330	0.0718	0.2419	-0.0018
78.5	3.9208	0.0866	0.2235	-0.0019
113	2.6586	0.0855	0.2499	-0.0005

It is clear that the fits are in reasonable agreements with experimental data. The fitted values of the four free fitting parameters mentioned above are presented in table (1). These values represent results of fits with over 95% confidence level. Few points are worth mentioning as far as the values of these fitting parameters are concerned. The first is that the values of three of the four fitting parameters (B,C, and ξ) are almost constant and they are almost not affected by the change in the electrode radius. The only parameter that seems to be affected by the area of the grounded electrode is the scaling parameter A. The second fact is that the secondary ionization coefficient γ is related to these parameters through the following equation. [15,16].

$$C = \ln \frac{A}{\ln(1+\frac{1}{\gamma})} \quad (3)$$

Consequently, one can obtain the first ionization coefficient from the fitted values of C,A, in each case.

The first ionization coefficient α can also be obtained by applying Townsend criterion using αd where d represents the inter-electrode distance, α represents the first ionization coefficient (pre-ionization coefficient). This factor of the ionization α can be computed experimentally from the slope of the rise current before the breakdown occur [17]. The Townsend criterion is given by [15-17]:

$$\mu = \gamma[\exp(\alpha d) - 1] = 1 \qquad (4)$$

where μ represents the reproduction coefficient. The reproduction coefficient can be calculated from equation (4), It is clear from table (2) that the values for μ of all cases are practically equal one. This is very important index is important in the sense that it confirms the fact the transition from non-self sustain to self-sustain condition and the breakdown voltage V_{bk} equal the external voltage applied V_{appl}. This fact demonstrates that the value of breakdown voltage as a threshold value for the breakdown take place in a certain conditions. At this moment the mechanism of the secondary ionization play with important role in the plasma. The effective secondary emission coefficient for cathode (electrode) ; emission is caused by positive ions, photons, and metastable atoms produced in the gas as a result of ionization and excitation of atoms by electrons. The discharge current is given by [15]:

$$i = i_0 \ \exp(\alpha d)/\{1 - \gamma[\exp(\alpha d) - 1]\} \qquad (5)$$

where i is the discharge current and i_0 represents the current produce by the external source as cosmic ray, UV... etc. Equation (4) is the denominator in equation(5). Indeed, at $\mu \geq 1$ this mean the breakdown condition is satisfied and the plasma became self-sustaining, *and* $i / i_0 > 0$ this means that for $i_0 = 0$ that is, the current flows even in the absence of an external source of electrons. Processes in the discharge gap ensure the reproduction of electrons removed by the field, without external trigger [15]. To ensure the self-sustained condition in the plasma one must have $V_{appl} > V_{bk}$ with $\mu > 1$. The values of γ , αd and μ are given in table (2) with breakdown voltage for all grounded electrodes area. With breakdown voltage for all grounded electrodes area. It may be worth pointing out that no explicit values for α are given. Instead, the values of αd are presented. This is due to the fact that radio frequency discharge involves two plasma sheaths instead of one. This may alter the correct assessment of the effective inter-electrode distance d.

Table (2) values of secondary ionization coefficient, αd, reproduction coefficient were calculated from equation (3) and (4) , for different values of the geometrical surface area of grounded electrode and breakdown voltage

$\mu \approx 1$	Reproduction coefficient(μ)	αd	γ	Grounded electrode surface area S (cm^2)	V_{bk}(Volt)
1	0.99999	4.5029	0.0112	7.06	136
1	0.99991	3.414	0.034	12.5	128.9
1	0.99999	3.1536	0.0446	28.2	112.1
1	0.9999	2.8197	0.0634	50.2	111.7
1	1	3.13664	0.0454	78.5	102.2
1	0.982243	2.057	0.144	113	99.13

The values of γ increase with the increase the grounded electrode area and the breakdown voltage increase with decrease of the grounded area. This can be explained by the fact that as the electrode area is increased, probability of the ion bombardment on the grounded electrode will also increase if one assumes that the ion density is constant. The values of γ against electrode area are plotted in Fig (4) the relation seem to be almost a linear one. The values of γ for all electrodes areas are consistent with those estimated in reference[17], and those made by Chapman [18] which gave the value of γ with argon and aluminum metal equal 0.12. From table(2) if $\gamma \sim 10^{-1} - 10^{-3}$, as the necessary condition for self-sustain discharge when $\ln\gamma^{-1}/\ln2 \approx \alpha d/\ln2$ (3-10) ionizing collisions along the path d [15], this condition is proved to be satisfied for all using electrodes used as in table (3).

The experimental data obtained to check the predictions made by Ashcroft and Mermin [19] which relates the value of the discharge current at the minimum breakdown potential to the electrons number density at the surface of the electrode material (n_e).

Table (3) shows the condition of the self-sustain in the discharge $\ln\gamma^{-1}/\ln2 \approx \alpha d/\ln2$

Grounded electrode surface area (cm^2)	$ln\gamma^{-1}/ln2$	$\alpha d/\ln2$
7.06	6.4804	6.4963
12.5	4.8783	4.925
28.2	4.4868	4.54
50.2	3.9083	4.0013
78.5	4.4612	4.5252
113	2.7959	2.9676

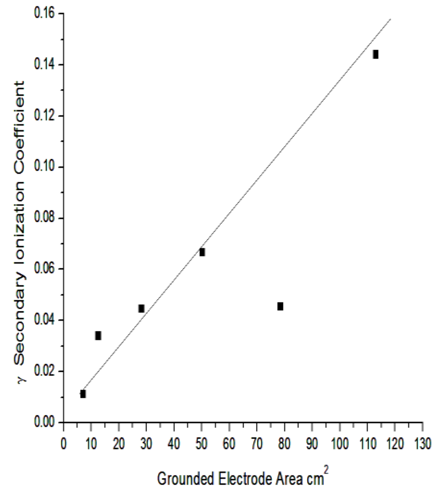

Fig.(4) The linearity of the secondary ionization coefficient γ versus different grounded electrode surface area

The discharge currents at the Paschen minimum in each case are obtained from calibrated oscilloscope pictures of the current waveform which are showed in Fig (5).

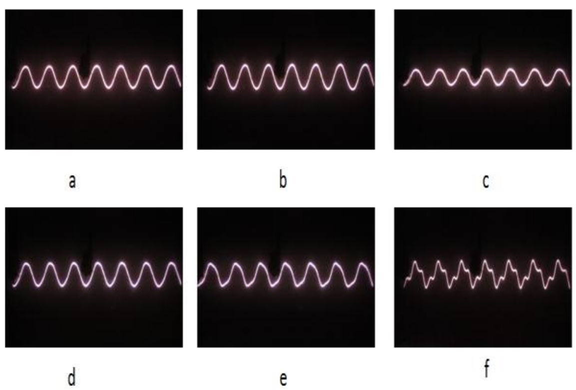

Fig.(5) Discharge current waveforms for ccp rf discharge with grounded electrodes where pictures from a to f with surface area 7.06, 12.5, 28.2, 50.2, 78.5 and 113 cm^2 at **pressure $p = 10\ Pa$ and the inter-electrode distance $d = 4\ cm$**

Figure (6) shows Breakdown current at Paschen minimum versus the calculated density of electrons for six grounded electrode n_e times the effective surface area of the grounded electrode S at the Paschen minimum (pd) for pressure 10 Pa at distance $d = 4\ cm$ .Calculated density of electrons in the aluminum electrode is taken from the Drude - model is equal $18.1 \times 10^{22}\ cm^{-3}$[12,19]. The plots of the breakdown current (at the Paschen minimum), against the density of electrons in the grounded electrode times the effective surface area of the grounded electrodes, for six electrode made from aluminum. The breakdown current represents the electron sea observed at the onset of the ccp RF glow discharge. The results are found to be proportional to the calculated effective density of electrons in the grounded electrode. When the grounded electrode area is decreased the smaller numbers of electrons are available from the surface and the breakdown current decreases proportionally. This suggests that the discharge current density is almost constant.

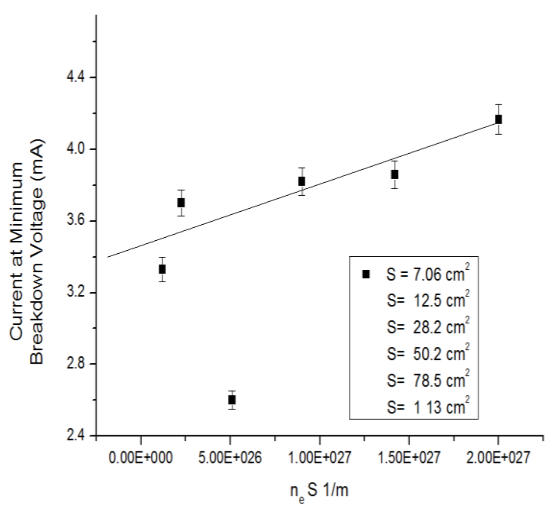

Fig.(6) Breakdown current at Paschen minimum versus the calculated density of electrons in the grounded electrode n_e times the effective surface area of the grounded electrode S at the Paschen minimum (pd) at pressure equal 10 Pa and $d = 4\ cm$

Conclusions

From above experimental results one may conclude that a modified Paschen curve which takes into account the indirect RF discharge which takes place via the chamber wall can provide a reasonable description of RF discharge breakdown data. The size of electrodes affects the overall scale of the breakdown potential but not the general shape of the pd–breakdown voltage relation. Fitted parameters in the proposed equation are used to calculate the second ionization and electrons reproduction coefficients. Both quantities tend to follow linear relationships to electrode area. The data support the predictions that the value of the breakdown current at the Paschen minimum is linearly related to the electrode area. The discharge current density at the breakdown threshold voltage appears to be independent of the electrode area.

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