

DEPENDENCE OF RF BREAKDOWN CURVE ON ELECTRODE GEOMETRY IN CCP REACTOR

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The results of experimental and theoretical study of RF capacitively coupled discharge breakdown in reactor for reactive ion etching of semiconductors are presented. Taking into account complex geometry of the reactor with asymmetric electrodes the main attention has been paid to influence of geometric factor on the breakdown curve. Experiments have shown that the geometry of the electrodes has impact on the breakdown curve only at lowest gas pressure (<50 mTorr). In cylindrical configuration the curve has a region of ambiguity, while for asymmetric configuration similar to GEC reference cell the low pressure part of the breakdown curve is almost vertical. The experimental data are compared to the numerical simulation results obtained using the particle-in-cell/Monte Carlo (PIC/MCC) code. The comparison shows qualitative consistence of the results with general tendency of theoretical curves to be slightly shifted to higher pressures that can be explained by simultaneous action of different kinds of electron emission from the electrodes, while we accounted only for secondary electron emission. Both theory and experiment show influence of secondary electron yield from different electrode materials (aluminum, steel, graphite) on the low-pressure part of the breakdown curve.

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INTRODUCTION

Gas discharge breakdown is one of the most basic problems of gas-discharge physics, which has been studying for more than 100 years [1-3]. Nevertheless, despite the long history the breakdown physics is not completely understood and permanently attracts attention of researchers [4-7].

The radio frequency (RF) discharge ignition is very specific case in which oscillatory motion of electrons between electrodes may cause dramatic change of Paschen curve [3,5]. The breakdown voltage drops significantly comparing to the DC breakdown when the electron oscillation amplitude became less than half of inter-electrode gap. Another unusual feature of the RF breakdown curve is the ambiguity region at low pressures where the discharge can be ignited not only by increase of the RF voltage amplitude but also by the amplitude decrease [3-7].

A number of researchers studied features of the RF breakdown curve experimentally and theoretically, so to the moment influence of different factors has been investigated such as kind of gas [7], oscillation frequency [2-4,6], spacing between electrodes [4,7], discharge chamber geometry [3,6]. It was also shown

experimentally that the electrode surface material has evident impact on the low-pressure part of the RF breakdown curve [8]. However, the influence of electron emission on the RF breakdown process in chamber with complex geometry has not been cleared.

The results of experimental and theoretical study of RF capacitively coupled discharge ignition in chambers of different shape are presented in this paper. The main attention is paid to influence of secondary electron emission and geometric factor on the breakdown curve.

1. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup used in our investigation is shown in Fig. 1. The experiments were carried out in two different configurations: cylindrical and similar to GEC reference cell. The sidewall of the vessel is made of metal. The RF power is coupled to the stainless steel bottom electrode with radius $R = 6$ cm via a matching box; the top one and side wall are grounded. The central part of the upper electrode is shower-like for gas feeding into the chamber. The vessel is evacuated by a turbo molecular pump down to a base pressure of about 10^{-5} Torr. The experiments were performed in the argon pressure range 20...700 mTorr. The RF power (13.56 MHz) is supplied by an RF generator with maximum output power of 500 W.

The main radius of the chamber is $R = 10$ cm and height $L = 7$ cm. Inter-electrode gap at the chamber axis is 4 cm. To transform the chamber to cylindrical configuration the stainless steel grid with the cell size 0.25 mm and optical transparency about 0.5 was installed (see Fig. 1), so the discharge was ignited in the chamber with inner diameter 12 cm and height 4 cm.

For measurement of the high-pressure part of the breakdown curve the gas pressure was fixed, and then the RF voltage was slowly increased until gas breakdown occurs. The low-pressure part of the curve may be multi-valued, therefore in this range we first decreased the gas pressure, then fixed the RF voltage value and then

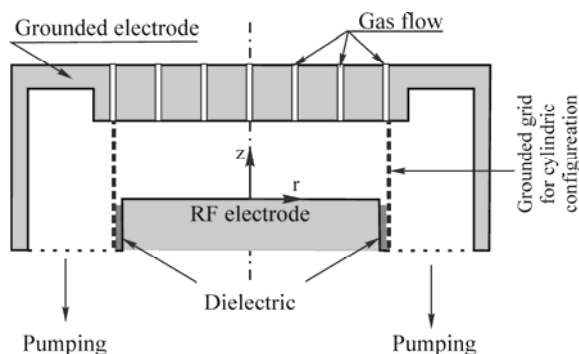


Fig. 1. Schematic diagram of the experimental set-up

increased the gas pressure slowly until gas discharge ignition occur. At the moment of the discharge breakdown the RF voltage shows a sharp change. The uncertainty in the measured breakdown voltage amplitude U_{br} was no more than 2% over the whole U_{br} range under study.

2. SIMULATION

The simulation was performed using two dimensional particle-in-cell (PIC) model implemented by Tech-X Copr. in OOPIC Pro code [9]. OOPIC Pro includes Monte Carlo collision algorithms for modeling collisions of particles with background gases that might result in the ionization of the background gases and the production of a pre-defined species of particle. The simulations were performed for argon gas. Each macro particle included one physical particle. In typical simulation ten thousands particles were used. The uniform gas temperature was set as 0.025 eV. The simulation grid and time steps were chosen reasonably small, that computing process ensures authentic physical results with minimal computing time. The simulation time step should be significantly less than the electron mean free time, than the grid cell crossing time by the fastest particles, and than the RF period. Thus the time step for the simulation was chosen as 10^{-10} s. The grid step was 1 mm.

As an initial condition of the breakdown we accounted for natural background ionization using random generation of electrons appearing uniformly over the entire volume of the chamber during one period of driving RF voltage. To determine the breakdown voltage we used condition of balance between creation of electrons by ionization and secondary emission and their loss to the walls. For each value of the gas pressure we searched the RF voltage amplitude providing unchanged mean number of electrons over several RF periods.

Vaughan secondary electron production model is used for electron impact on the electrode surface that includes energy and angular dependence of the emission yield [10]. In the described simulations we assume that 10% of the primary electrons are reflected from the surfaces so the normal component of the incident particle's velocity has its sign reversed. Another 10% of the incident particles are assumed to be scattered, i.e. all components of the particle's velocity are scaled by uniform (0,1) random values keeping total energy unchanged.

3. RESULTS AND DISCUSSION

Fig. 2,a shows the breakdown curves of RF discharge in cylindrical chamber in argon measured with the upper electrode made of different materials (aluminium, stainless steel and graphite). For high pressures (more than 100 mTorr) the observed breakdown voltages match for the all applicable materials, while at low pressures the discharge curves are significantly affected by the electrode material. The Fig. 2,a shows that with the increase of the electron emission yield the low-pressure part of the breakdown curve is shifted to the left and a bit down. In all the experimental curves the region of ambiguous dependence of the RF breakdown voltage on the gas pressure is clearly visible at the lowest pressures.

The results of systematic calculations of the RF breakdown curve for different secondary $e-e$ emission yields δ are shown in the Fig. 2,b. The simulations were performed for low pressures (30...300 mTorr) in the RF voltage range 80...500 V.

One can see from the Fig. 2,b that the simulation results are qualitatively consistent with the experimental data. All the breakdown curves demonstrate multivalued dependence at lowest pressures and coinciding right-hand branches. Similarly to the experimental curves the calculated dependences are shifted to the left and a bit down with δ growth.

General analysis for all the used electrode materials shows that all the theoretic curves are slightly shifted to the right in relation to the corresponding experimental curves. The right-hand branches of the theoretic curves are approximately 20 V higher then the experimental. Presumably, this discrepancy appears since the model takes into account only the electron induced secondary electron emission, while for accurate description of the RF breakdown it is of course necessary to consider all types of electron emission: $e-e$ and $i-e$ emissions as well as electron emission caused by photons and metastable atoms.

Fig. 3,a,b shows the breakdown curves of RF discharge in argon measured for cylindrical and for GEC cell configurations as well as simulation results for the mentioned chambers. Both the experimental and the theoretical results demonstrate that the chamber extension with the constant inter-electrode gap causes the deflection of the low-pressure part of the breakdown curve.

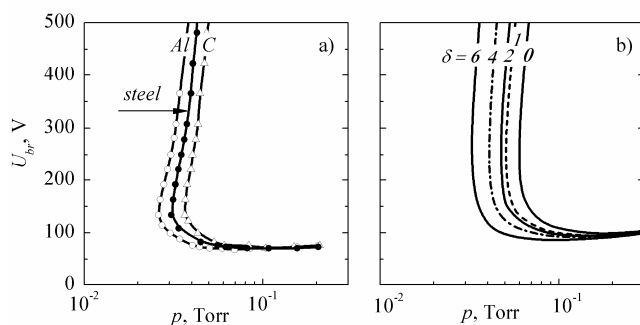


Fig. 2. Breakdown curves for different top electrode materials: a) experimental data, b) simulation result

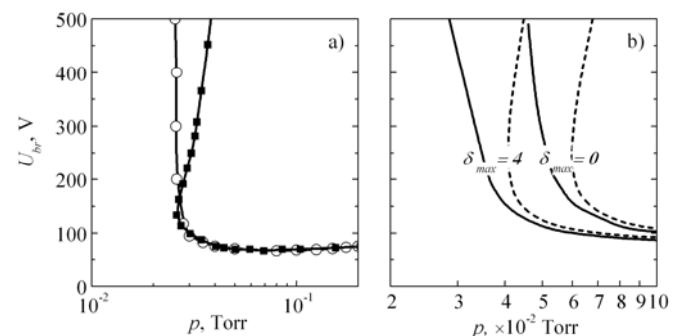


Fig. 3. Breakdown curves for two chamber configurations (similar to GEC cell – solid curves, cylindrical – dash curves): a) experimental data, b) simulation result

The shift of the curve to lower pressures at high voltages could be explained by appearing of longer trajectories of electron oscillation between the bottom electrode and upper corner of the chamber. The increase of the electron path length L leads to decrease of the breakdown pressure p in order to keep the similarity parameter pL constant.

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ВЛИЯНИЕ ГЕОМЕТРИИ ЭЛЕКТРОДОВ ВЧ-РЕАКТОРА НА КРИВУЮ ЗАЖИГАНИЯ РАЗРЯДА

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Представлены результаты экспериментальных и теоретических исследований кривой зажигания ВЧ-разряда в реакторе для ионного реактивного травления. С учетом сложной геометрии реактора с асимметричными электродами основное внимание было уделено влиянию геометрического фактора на кривую зажигания разряда. Эксперименты показали, что геометрия электродов оказывает существенное влияние на кривую зажигания в области низких давлений рабочего газа (<50 мТорр). Для цилиндрической геометрии камеры в области низких давлений существует область неоднозначности кривой зажигания, в то время как для асимметричной конфигурации близкой к ГЕС ячейке наблюдается практически вертикальный рост напряжения зажигания разряда с уменьшением давления газа. Наблюдается качественное согласие численных расчетов, полученных с использованием particle-in-cell/Monte Carlo (PIC/MCC) кода, с экспериментом. Общую тенденцию смещения расчетных кривых зажигания в область более высоких давлений можно объяснить необходимостью корректного учета различных видов электронной эмиссии с электродов в дополнение к учетной нами вторичной e - e -эмиссии. И теория, и эксперимент показывают существенное влияние вторичной электронной эмиссии на кривую зажигания ВЧ-разряда в области низких давлений.

ВПЛИВ ГЕОМЕТРІЇ ЕЛЕКТРОДІВ ВЧ-РЕАКТОРА НА КРИВУ ЗАПАЛЮВАННЯ РОЗРЯДУ

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Представлені результати експериментальних та теоретичних досліджень кривої запалювання ВЧ-разряду в реакторі для іонного реактивного травлення. З урахуванням складної геометрії реактора з асиметричними електродами основну увагу було приділено впливу геометричного фактора на криву запалювання розряду. Експерименти показали, що геометрія електродів робить істотний вплив на криву запалювання в області низьких тисків робочого газу (<50 мТорр). Для циліндричної геометрії камери в області низьких тисків існує область неоднозначності кривої запалювання, в той час як для асиметричної конфігурації близької до ГЕС осередку спостерігається практично вертикальне зростання напруги запалювання розряду при зменшенні тиску газу. Спостерігається якісна згода чисельних розрахунків, отриманих з використанням particle-in-cell/Monte Carlo (PIC / MCC) коду, з експериментом. Загальну тенденцію зсуву розрахункових кривих запалювання в область більш високих тисків можна пояснити необхідністю коректного врахування різних видів електронної емісії з електродів в доповнення до врахованої нами вторинної e - e -емісії. Як теорія, так і експеримент показують істотний вплив вторинної електронної емісії на криву запалювання ВЧ-розряду в області низьких тисків.