ABOUT PECULIARITIES OF SELF-BIAS VOLTAGE FORMATION IN PLASMA-CHEMICAL REACTORS WITH CONTROLLED MAGNETIC FIELDS

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The peculiarities of self-bias voltage formation in plasma-chemical reactors (PCR) with controlled magnetic fields have been investigated. The dependences of self-bias voltages on the values and configurations of magnetic fields in PCR, as well as, on the pressures, gas flows, discharge currents, discharge RF voltage drops are obtained.

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INTRODUCTION

During recent decades plasma-chemical technologies find expanding applications in engineering and industry. Plasma-chemical etching is successfully applied in the technological processes in manufacturing of power devices, products of microelectronics, micromechanics, computer engineering, microwave techniques, etc. [1]. However, the processes, taking place in plasma-chemical reactors, are insufficiently studied. This is primarily due to the complexity of diagnostic of phenomena which occur in the chemically active multi-component plasma. In particular, when we investigating the plasma optical spectra, in most cases it has been succeeded to identify only the most intense lines belonging to the excited atoms [2]. Discharges in the chemically active plasma often can cause chemical reactions, which are not specific for normal chemical processes. Therefore, the optical spectra of molecules formed in these processes are absent in existing tables of molecular spectra/ For example, in the process of silicon etching in the fluorine-containing plasma (SF_6) the molecules such as SF_5, SF_4, SF_3, SF_3O, SF_2O_2, SF_2O, SFO etc. are formed [2]. The problems of electron- and ion stimulation effect on the silicon etching rate, as well as, the influence of stimulating particles on the etching rate of different materials are little-studied. There is a lack of information in the literature on the self-bias voltage (U_{bias}) depending both on the basic parameters of the reactive plasma produced in the plasma-chemical reactor and the influence on it of configurations and magnetic fields. At the same time, the constant component of U_{bias} is approximately equal to the alternating voltage amplitude and, practically, determines the average energy of ions bombarding the target [3, 4].

A purpose of the present paper is to study the influence of controlled magnetic field configurations and different discharge parameters and conditions on the self-bias voltage in plasma-chemical reactors (PCR).

1. EXPERIMENTAL

The self-bias voltage is a direct-current voltage arising in the case of the RF discharge between the active and grounded electrode. It occurs because of different mobility (diffusion rate) of electrons and ions in the plasma of high-frequency discharges in the controlled magnetic fields and different electrode areas. Under specific conditions and intensity values of magnetic fields and their configurations it is possible to magnetize electrons and thus to decrease significantly the velocity of electron transfer from a central electrode to an outer electrode in the constant electric field, created by the RF discharge between two electrodes, having different areas. In other cases, vice versa, the velocity of electron transfer to the outer (grounded) electrode can be increased by applying a divergent magnetic field and therewith increasing the self-bias voltage. Application of low magnetic fields permits to magnetize only electrons, not ions, [5]. Therefore, we will consider the controlled magnetic field effect on the electrons only. Investigations were carried out with the use of the devices described in [2, 6].

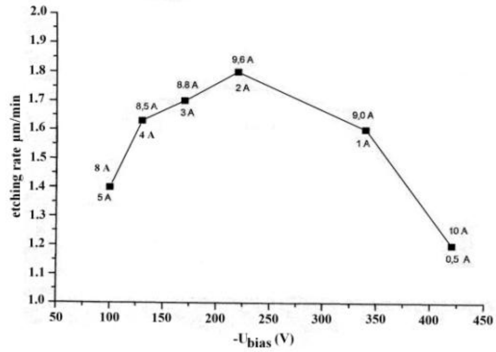


Fig. 1 .Silicon etching rate as a function of the self-bias voltage

As is shown in the silicon etching rate has a maximum and decreases with negative voltage increasing to above 250 V under the same other discharge conditions (Fig. 1). Under discharge conditions described in the change of self-bias voltage was performed by controlling the lower coil current with a constant current in the middle magnetic field coil. However, there is an ambiguity since the etching rate also changes with magnetic field intensity changing. In this connection it is necessary to know how other discharge parameters influence on the self-bias voltage.

Let us consider the mechanisms of formation, magnitude and polarity of the self-bias voltage depending on the plasma-chemical reactor design, magnetic field value and configuration, discharge parameters in the plasma-chemical reactors.

In the plasma-chemical reactors, where the chemically active plasma is excited without magnetic field, the negative self-bias voltage increases proportionally to the difference of areas of the active and grounded electrodes. According to ref. [3] in the case of RF discharges the constant component of U_{bias} is approximately equal to the alternating voltage amplitude and, practically, determines the average energy of ions bombarding the target. However, in every concrete reactor the self-bias voltage increases with discharge current increase and can vary depending on the pressure value in the reactor, kind of gas and components of working gas mixture. Besides, by reducing the area of the grounded electrode, to the size smaller than that of the active electrode, it is possible to obtain on it a positive bias as, for example, in the devices of 08ПХТ-100/10-006 type, which were widely applied in the electron industry enterprises. In such devices the plasma-chemical etching was electron-stimulated but, the polymer films, formed during etching the process layers of microelectronics products, were deposited. Then the etching rate was sharply decreasing that leaded to a significant etching inhomogeneity. In plasma-chemical reactors, developed in the Institute for Nuclear Research of NASU, the areas of active electrodes were, generally, smaller than these of grounded electrodes. Therefore a negative self-bias took place on the active electrodes that leaded to the ion stimulation in the process of material etching.

Let us consider how the self-bias voltage is changing with the use of a short trihedral prism as an active electrode of (110 x 120) mm^2. This variant of PCRs was used to reach high values of self-bias voltage and to clean the surface of materials being applied in microelectronics [10]. The length of the outer grounded electrode was 450 mm with the outer cylinder of 200 mm in diameter. Fig. 2 (curve 1) represents the self-bias voltage as a function of the working gas (sulfur hexafluoride SF_6) pressure in the PCR under RF discharge (13.56 MHz) without magnetic field. The volume of gas charged in the reactor was constant and controlled by the oil flow meter, and the pressure in the discharge chamber was controlled by measuring the pumping speed. The RF oscillator power was also constant (1 kW). By increasing the pressure in the reactor from 10^{-2} to 10^{-1} Torr, without magnetic field, the negative self-bias was decreased from -640 to -290 V. However, in this case the discharge current sharply was decreased from 15 A to 11.5 A (Fig. 3, curve 1) and almost stabilized at a defined level (11.5) with pressure changing from $4{\cdot}10^{-2}$ to $1{\cdot}10^{-1}$ Torr. So, the curve in Fig. 2, representing the self-bias voltage as a function of the pressure in the PCR, is ambiguous.

The self-bias voltage and, consequently, the ion energy can be controlled using the controlled magnetic fields and changing their configuration. By including the magnetic field of $40{\cdot}10^2$ A/m and increasing the pressure from 10^{-2} to10^{-1} Torr the self-bias voltage decreases from -600 to -130 V (see Fig. 2, curve 2). The discharge current decreases from 14.5 to 11.5 A under pressure of $4{\cdot}10^{-2}$ Torr, then it becomes stabilized at this level to $8{\cdot}10^{-2}$ Torr and again sharply decreases to 10 A under pressure of 10^{-1} Torr. All this evidences on the lowering of the degree of plasma ionization and, respectively, on the plasma volume resistance increasing (see Fig. 3, curve 2).

The magnetic field increase to $80{\cdot}10^2$ A/m leads to another result. The self-bias voltage is practically constant (at a level of 220 V) during pressure increasing (see Fig. 2, curve 3). And the current increases from 9 to 10 A Torr with pressure changing from 10^{-2} Torr to $5{\cdot}10^{-2}$ Torr, and after became stabilized (see Fig. 2, curve 3).

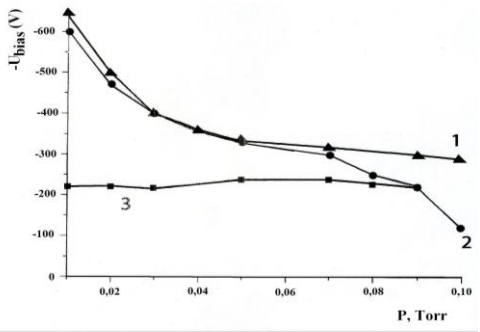


Fig. 2. Self-bias voltage as a function of the pressure (1 – magnetic field intensity (1 – H = 0 A/m; 2 – H = $40{\cdot}10^2$ A/m; 3 – H = $80{\cdot}10^2$ A/m)

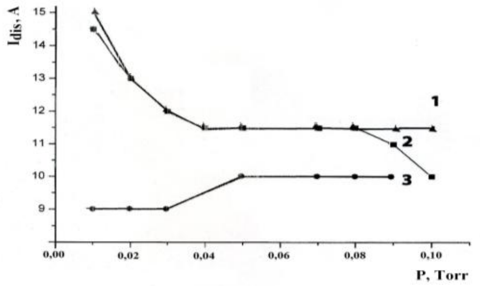


Fig. 3. Discharge current as a function of pressure (1 – H = 0 A/m; 2 – H = $40{\cdot}10^2$ A/m; 3 – H = $80{\cdot}10^2$ A/m)

In the self-bias voltage has been measured as a function of the discharge RF voltage drop under different argon pressures in the reactor that corresponds to the discharge current increase. However, it should be noted, that any appreciable dependence of the constant self-bias voltage in the discharge without magnetic field on the pressure changing from 1.6 to 500 mTorr is not observed. The curves obtained in for three values of gas pressure in the discharge are almost equal and linear. To a first approximation they obey to the law noted in [3].

The constant component (self-bias voltage) U_{bias} is approximately equal to the alternating voltage amplitude and, practically, determines the average energy of ions bombarding the target [3].

Configurations and values of magnetic fields used in [3] were changed within wide ranges. Fig. 4 shows several variants of magnetic field configurations and different distributions of magnetic field values measured along the active electrode. Fig. 4,a shows the dependence of the magnetic field intensity at the prism face for one of modifications of the PCR manufactured by request of the MSRIRM (Minsk, Belarus). When the current in the coil is changing from 0 to 4.5 A the magnetic field intensity increases from 0 to $88{\cdot}10^3$ A/m. And in the case of the discharge current equal to 6 A the self-bias voltage decreases to 0 V at the magnetic field intensity of $80{\cdot}10^3$ A/m.

Figs. 4,b-c represents different variants of magnetic field configurations and distributions along the working surface of the prism on which the samples to be plasma treated were installed depending on the posed tasks: from soft etching without radiation damage to sputtering of different materials.

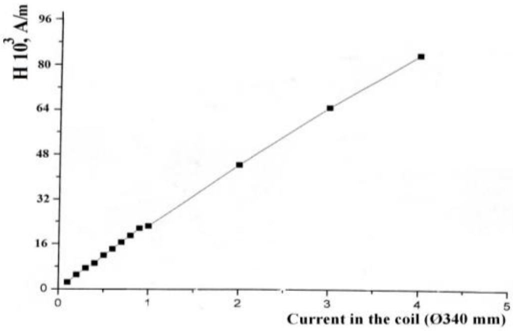
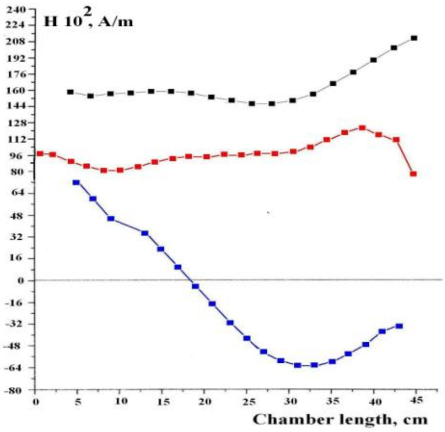


Fig. 4,a. Magnetic field intensity as a function of the current in the coil (Ø340 mm)



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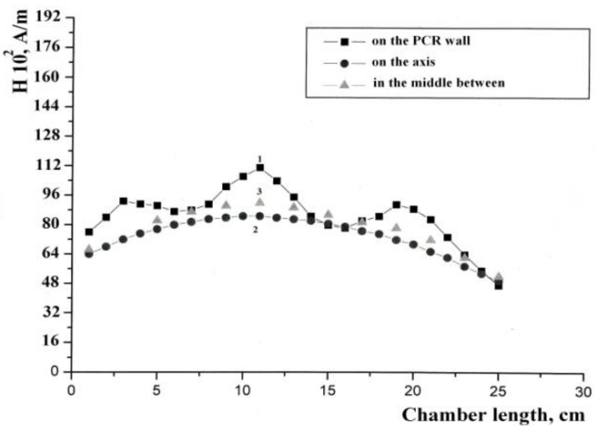
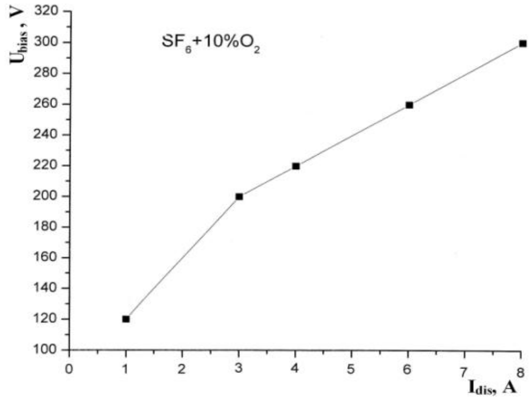


c

Fig. 4. b-c. Magnetic field intensity distribution along the PCR length

Fig. 5 represents the self-bias voltage as a function of the current value in the lower coil at a constant current of 2 A (H = $80\cdot10^2$ A/m) in the upper coil. It was possible to control the self-bias voltage from -120 V (without a current in the lower coil) to -300 V.

In this case the current in the lower coil was increased 7 A and was connected in antiphase with the current in the primary coil. Figs. 5, 6 show the change of U_{bias} in the argon plasma depending on the polarity and value of the current in the lower and upper coils (the current in the middle coil, argon pressure and discharge current being constant). Here the self-bias value is changing from 100 V in the case of in-phase connection of coils, and to -160 V in the case of antiphase connection of coils.



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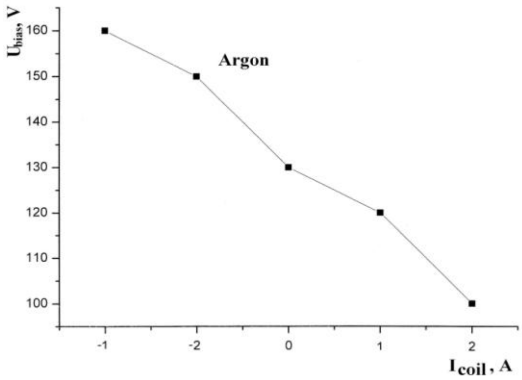

b

Fig 5. a – self-bias voltage as a function of the current in the lower coil; b – self-bias voltage as a function of current direction in the coil

Fig. 6 (curve 1) shows the self-bias voltage (U_{bias}) as a function of the discharge current value in the CCl_4 + Ar plasma with the constant magnetic field of $40\cdot10^2$ A/m. As the discharge current increases from 3 to 10 A, the self-bias voltage is changing from -80 to -220 V. The connection of an additional 440 kHz oscillator under the same conditions permitted to increase sharply the negative self-bias voltage from -280 to -380 V (with a current of 4 A from the additional oscillator) (see Fig. 6, curve 2). To increase U_{bias} for the attainment of sputtering, the additional oscillator of a 440 kHz frequency and controlled power to 4 kW was connected. Thus, it has been succeeded to increase the self-bias voltage from -20 to -1000 V and more.

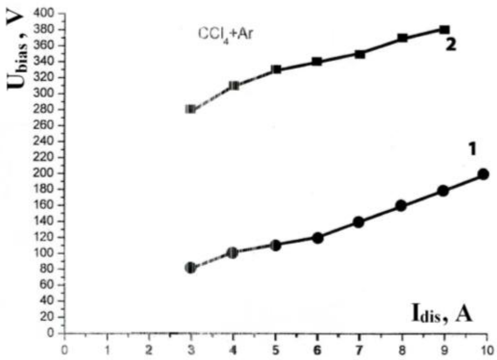

Fig. 6. Self-bias voltage as a function of the discharge current (1 – without additional oscillator; 2 – with additional oscillator, of 440 kHz frequency)

Using the additional oscillator it is possible to sputter not only the metals and semiconductors with a relatively good conductivity but, also, dielectrics such as lithium tantalate $LiTaO_3$, strontium tantalate $TiSrO_3$ etc., having the chemical bond of about 9.5 eV.

Semiconductors having a low conductivity, e.g. gallium arsenide, gallium phosphide and nonconducting ceramics, also are well-sputtered materials. This is due to more intense escaping onto the grounded electrode of electrons being under a longer action of a comparatively low-frequency voltage of 440 Hz. At such frequencies the ions are simultaneously exposed to the action of the field which is longer by a factor of 31 as compared to the action of the RF field having a frequency of 13.56 MHz. During comparatively long time of the field action on the ions they have time to displace in the space between the active and grounded electrodes and to remove the negative surface charge from dielectrics and low-conducting semiconductors. There still more is the influence of such a field on the electrons which have time to get the central (active) electrode and to compensate a positive charge which appears on the surface of the sample being treated. Due to this effect the etching rate of dielectrics, semiconductors and metal films can be increased.

Practically, the linear increase of the self-bias voltage (other parameters being constant) is observed when in the SF6 gas a high-frequency discharge occurs with discharge current increasing (Fig. 7). In the case of discharge current increasing from 6 to 14 A the self-bias voltage increases from -110 to -240 V.

The magnetic field intensity increase from 0 to $12 \cdot 10^3$ A/m (other conditions in the discharge being constant) leads to the self-bias decrease from 270 to 120 V (Fig. 8). According to the investigation results, the magnetic field increase to $80 \cdot 10^3$ A/m decreases the self-bias voltage to 0. This is because the complete "freezing" of electrons stops their diffusion onto the large surface area of the outer grounded electrode. And this effect is a main one: it means that the electron diffusion in the magnetic field can be controlled.

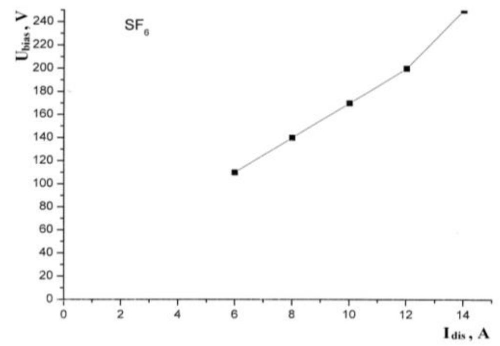

Fig. 7. Self-bias voltage as a function of the discharge current

It is possible to decrease, as well as, to increase the electron diffusion rate, depending on the magnetic field intensity and configuration, and thereby to control the self-bias voltage and, consequently, the average energy of chemically active ions. Simultaneously with magnetic field intensity increasing, in the case of a "mirror" magnetic field configuration, the time of electron existence in the plasma volume also increases that leads to the increase of the degree of dissociation and ionization of the chemically active plasma. This is explained by the fact that electrons move in the spiral orbits along the magnetic field and have time to gain much energy before escaping from the plasma volume. Thus the content of chemically active radicals and ions in the plasma-chemical reactor increases, and, consequently, the sample etching rate increases too. And, vice versa, the rapid electron escape onto the grounded electrode increases the self-bias voltage, but decreases the material etching rate.

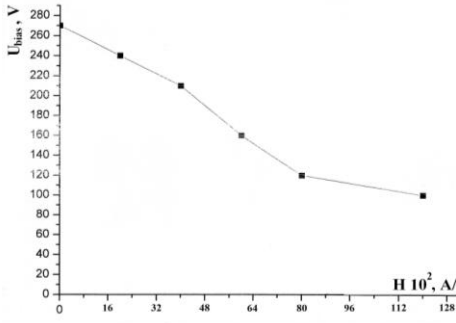

Fig.8. Self-bias voltage as a function of the magnetic field

When the working gas flow rate increases from 4 to 19 *l*/h, with the discharge current of 8 A, pressure in the chamber of 0.05 Torr, magnetic field intensity of $12 \cdot 10^3$ A/m and with the discharge in the SF6 gas, the self-bias voltage first (to 8 *l*/h) decreases from -100 to -60 V and then becomes almost stabilized (Fig. 9).

This indicates on the inefficiency of the use of high gas flow rates, on the unreasonable discharge into the atmosphere of a considerable amount of unused chemically active gases and on the rise in cost of their utilization.

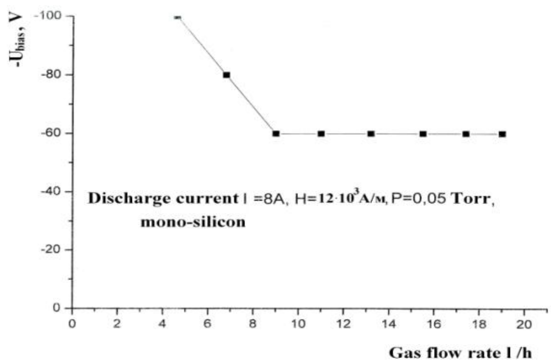

Fig. 9. Self-bias voltage as a function of the gas flow in the discharge

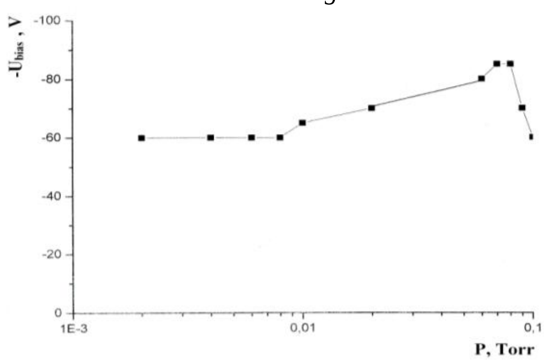

Fig. 10. Self-bias voltage as a function of the working gas pressure in the PCR

Results of investigations on the dependence of self-bias voltage on the pressure in the discharge chamber are given in Fig.10. The pressure increase by two orders of magnitude from $2\cdot10^{-3}$ to $8\cdot10^{-2}$ Torr (other parameters in the discharge chamber being constant) leads first to the insignificant increase of the self-bias voltage from -60 to -80 V and then to the sharp decrease to -60 V. The effect observed can be related with the electron mean free path decrease caused by the pressure increase in the chamber. Because of electron-atom collisions the electrons can not gain the energy sufficient for ionization and dissociation of working gas atoms and molecules. As a result, the degree of ionization and dissociation in the PCR decreases. Thus the concentration of free electrons decreases and the number of electrons coming onto the grounded chamber walls decreases too. The pressure in the chamber was varying by closing softly the diffusion pump valve without changing the working gas flow rates.

Fig. 11 shows the self-bias voltage as a function of the discharge voltage drop value. The discharge was performed in the SF_6 gas under pressure of $5\cdot10^{-2}$ Torr. The self-bias voltage increases approximately linearly with discharge voltage drop decreasing but at the angle of slope ~ 60° , not near 45°. This points to the fact that there are exiting other mechanisms of self-bias voltage formation, since, according to [3], in the cases of RF discharges without magnetic field the constant component of U_{bias} is approximately equal to the alternating voltage amplitude.

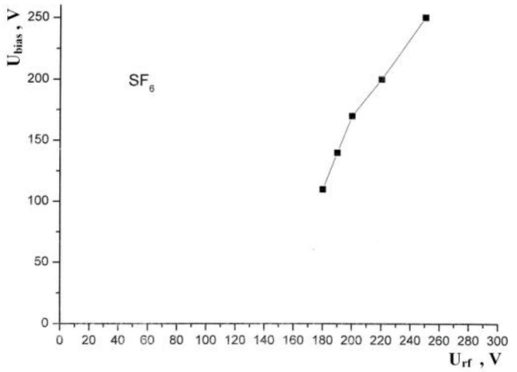

Fig. 11. Self-bias voltage as a function of the RF discharge voltage drop

In the presence of magnetic fields U_{bias} = ~100 V at the RF voltage pressure of ~ 180 V. This is evidence of a significant magnetic field influence on the electron diffusion and, consequently, on the self-bias voltage value. Besides, both the magnetic field values and their configurations exert influence on the self-bias voltage values.

CONCLUSIONS

The self-bias voltage caused by the RF discharges in controlled magnetic fields, with other discharge parameters being constant, depends of both the intensities of magnetic fields and their configurations. By changing the configuration and intensity of magnetic fields it is possible to control the self-bias voltage from 0 to 1000 V. The connection to the discharge of the additional oscillator with frequencies of 50 to 500 kHz also exerts significant influence on the self-bias voltage values.

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ОБ ОСОБЕННОСТЯХ ОБРАЗОВАНИЯ НАПРЯЖЕНИЯ АВТОСМЕЩЕНИЯ В ПЛАЗМОХИМИЧЕСКИХ РЕАКТОРАХ С УПРАВЛЯЕМЫМИ МАГНИТНЫМИ ПОЛЯМИ

В.В. Гладковский, О.А. Федорович, Б.П. Полозов, М.П. Кругленко

Экспериментально исследованы особенности образования напряжения автосмещения в плазмохимических реакторах (ПХР) с управляемыми магнитными полями. Получены зависимости напряжений автосмещения от величин и конфигураций магнитных полей в ПХР, а также от давлений, расходов газов, токов в разрядах, падений ВЧ-напряжений на разрядах.

ПРО ОСОБЛИВОСТІ УТВОРЕННЯ НАПРУГИ АВТОЗМІЩЕННЯ В ПЛАЗМОХІМІЧНИХ РЕАКТОРАХ З КЕРОВАНИМИ МАГНІТНИМИ ПОЛЯМИ

В.В. Гладковський, О.А. Федорович, Б.П. Полозов, М.П. Кругленко

Експериментально досліджені особливості утворення напруги автозміщення в плазмохімічних реакторах (ПХР) з керованими магнітними полями. Отримано залежності напруги автозміщення від величин і конфігурацій магнітних полів в ПХР, а також від тисків, витрат газів, струмів у розрядах, падінь ВЧ-напруг на розрядах.