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SIMULATION OF THE IGNITION OF A LOW PRESSURE RF CAPACITIVE DISCHARGE

V.A. Lisovskiy[*,**], **J.-P. Booth**[*]
[*]*Ecole Polytechnique, Palaiseau, France*
[**]*V.N. Karazin's Kharkiv National University, Ukraine*

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This paper reports the results of a theoretical treatment of RF gas breakdown. We present simulated breakdown curves for low-pressure RF discharges in argon over a broad range of gas pressures between parallel-plate electrodes. Analytical formulas for the electron transport coefficients in argon obtained from a Boltzmann code are presented. We solved the Boltzmann equation for argon and determined the frequencies of elastic and non-elastic collisions of electrons with argon, the energy fraction transferred to the atom on collision д as functions of the ratio of the electric field strength to the gas pressure *E/p*, the frequency of energy loss by electrons in collisions with argon atoms v_i. We found that the condition $v_u = \omega$ corresponds to the minimum of the RF breakdown curve. We may use the ionization frequency н_i as a function of the effective electric field E_{eff} only for modelling of the right-hand sides of RF breakdown curve. The ionization frequency н_i as a function of the instantaneous electric field $E_a\cos(\omega t)$ must be used for the prediction of RF breakdown voltage values to the left of the minimum of the breakdown curve.

A gas breakdown in an RF field occurs when the number of charged particles generated within the volume of the discharge gap through ionizing molecules via electron impact is greater than the number of particles having left this volume because of diffusion and drift in the RF electric field. This process is governed by the equation of charged particle balance in cylindrical geometry:

$$\frac{\partial n_e}{\partial t} = \nu_i n_e + D_e \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial n_e}{\partial r}\right) + \\ + D_L \frac{\partial^2 n_e}{\partial z^2} - V_e \cdot \nabla n_e \cdot \cos(\omega t) \quad , \qquad (1)$$

where n_e is the electron density, t is time, $\nu_i = \alpha \cdot V_e$ is the rate of the gas molecule ionization through electron impact, α is the first Townsend coefficient, D_L and D_e are the coefficients of electron diffusion along and across the electric field, respectively, r and z are the radial and axial co-ordinates, V_e is the electron drift velocity, $\omega = 2\pi f$ is the angular frequency, f is the RF generator frequency.

In order to model the gas breakdown, we need to know the transport coefficients of electrons in the gas, such as α, D_L, D_e and V_e. These coefficients were determined by solving the Boltzmann equation for argon. The values of the electron transport coefficients in argon obtained from the Boltzmann code were approximated with the following formulas:

$$\alpha = 1.6\cdot 10^3 \cdot p \cdot \exp\left(-\frac{19.0}{(E/p)^{0.25}} - 0.02\cdot (E/p)^{0.65} \right) [\text{cm}^{-1}\text{Torr}^{-1}]$$

$$V_e = (E/p)\cdot 4\cdot 10^5 \cdot \left(8 + 5\cdot 10^{-5}\cdot (8\cdot E/p)^{1.5}\right)^{-0.3} \ [\text{cm/s}],$$

$$D_e = \left(2\cdot 10^6 + 10^4\cdot (0.025\cdot E/p)^{1.8}\right)/p \ [\text{cm}^2\,\text{Torr s}^{-1}].$$

The equation (1) was solved using the FEMLAB program.

Let us consider first the discharge gap between plane parallel electrodes. The lower electrode ($z = 0$) is powered, the RF voltage $U_{rf} = U_{rf0}\cos(\omega t)$ being fed to it, the upper electrode ($z = L$ =23 mm) is grounded. Both electrodes have a diameter of 10 cm. The lateral walls of the discharge tube are made of a dielectric, and are at floating potential. Initially we disregarded secondary electron emission from the surface of the electrodes, i.e., the following boundary conditions were used for the electron density at electrodes and tube walls:

$$n_e(R,z) = 0\,, \quad n_e(r,0) = 0\,, \quad n_e(r,L) = 0 \qquad (2)$$

The initial value of the electron density was taken as $n_{e0} = 10^7$ cm^{-3}. All calculations were performed for the first 30 periods of the RF field. The RF voltage at the lower electrode was varied in order to find the value at which the average value of the electron density at the discharge centre remained constant in time after the first 10 periods of the RF field, i.e. $\frac{\partial n_e}{\partial t} = 0$. This value of the RF voltage was taken as a breakdown RF voltage. We observe such a situation in Fig. 1, depicting the temporal dependence of the electron density at the centre of the discharge gap.

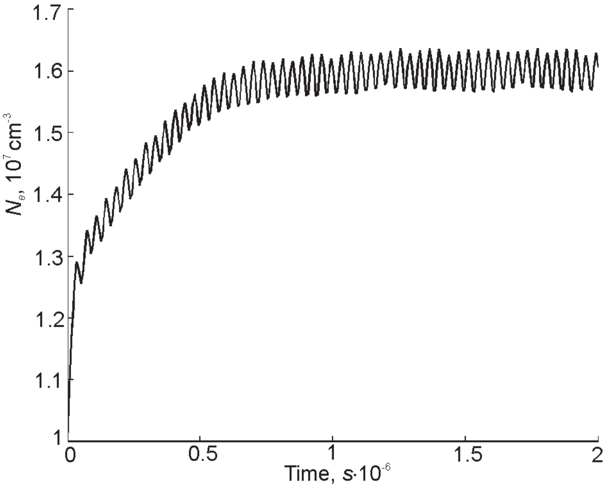

Fig. 1.Plasma density at the discharge gap center against time for p = 1 Torr, U_{rf} = 79.1 V.

For RF voltages below the breakdown threshold we observe a quick decrease of the electron density within the entire gap, because the electron losses dominate over their generation and therefore the RF discharge does not ignite. If we fix the RF voltage at the lower electrode above the breakdown value, then the electron density will increase with time quickly, because the number of electrons generated under ionisation will exceed the number of electrons lost at the electrodes and tube walls due to the drift in the electric field and diffusion. In Fig. 2 we see the variation of the axial profile of the electron density during

one (the last considered) period of the RF field. It is clearly seen that the axial profile of the electron density during

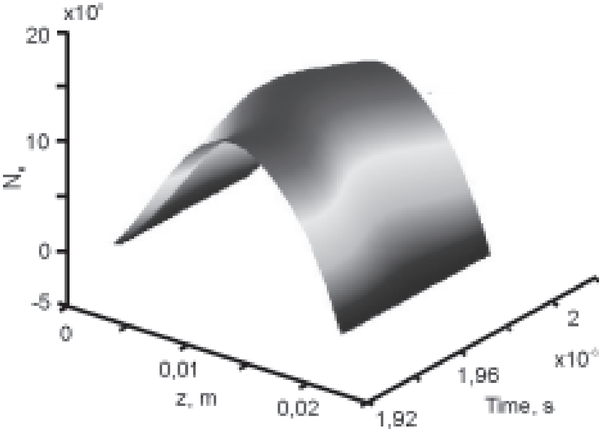

Fig. 2. Variation of the axial profile of the electron density during the 30-th period of the RF field for p = 1 Torr,

one (the last considered) period of the RF field. It is clearly seen that the axial profile of the electron density possesses a bell-like shape performing oscillations during the RF field period from one electrode to another. Calculations were also performed including secondary electron emission from the surface of the electrodes. The following condition was assumed:

$$\gamma \cdot \left(J_{Diff} + J_{Drift}\right) = J_S \,, \tag{3}$$

where γ is the coefficient of secondary electron emission, J_{Diff} is the diffusive flux of electrons to the surface of the electrodes, J_{Drift} is the electron flux to the surface of the electrodes caused by the drift motion in the RF field, J_S is the flux of secondary electrons emitted by the surface of the electrodes. The values of the coefficient γ for the aluminum electrode were taken from the papers [2, 3]. The coefficient γ is a function of the electron energy; the electrode emits electrons only during that half-period when the electron cloud moves towards this electrode and bombards its surface. During the second half-period the electron emission takes place only from the surface of the other electrode.

Figure 3 presents the experimentally observed breakdown curve of the RF discharge in argon for L = 23 mm, published in the paper [1], as well as the present results of modelling. The results of numerical modelling agree with the measured data satisfactorily. The RF breakdown voltage values obtained through modelling are higher than the measured ones.

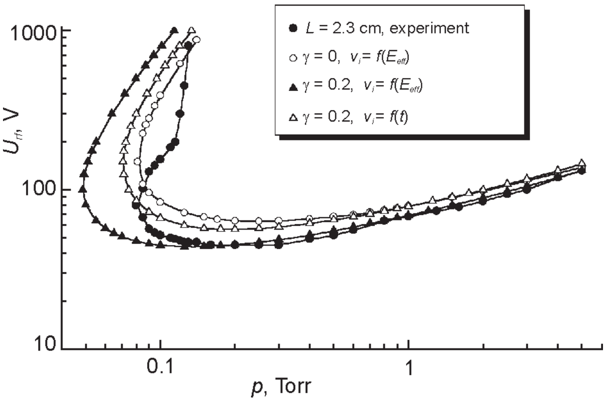

Fig .3. Breakdown curves of the RF discharge for L = 2.3 cm: solid circles are experimental data [1], open circles are our results for γ = 0 (electron density at electrodes equals to zero) and ionization frequency ν_i is function of effective electric field E_{eff} , solid triangles are for γ = 0.2 and ionization frequency ν_i is function of effective electric field E_{eff} , open triangles are for γ = 0.2 and ionization frequency ν_i is function of instantaneous electric field $E_a\cos(\omega\, t)$.

Figure 4 shows simulated values of the RF breakdown voltage for the gas pressure p = 0.2 Torr as a function of the secondary electron emission coefficient. The best agreement with the experiment was obtained with γ = 0.2.

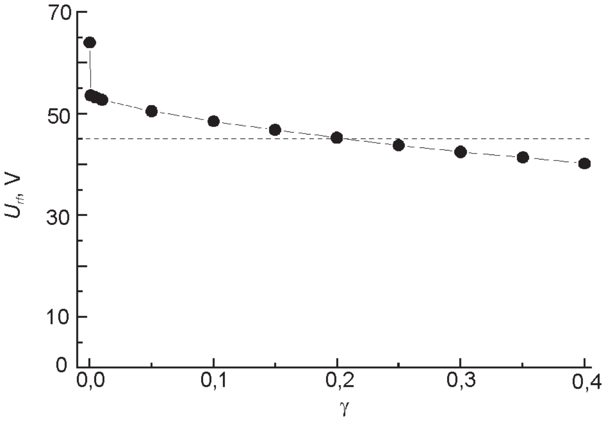

Fig. 4. Breakdown voltages of the RF discharge as a function of γ for p = 0.2 Torr: dashed line is experimental breakdown voltage.

We solved the Boltzmann equation for argon and determined the frequency of elastic collisions of electrons with argon atoms ν_{el}, the total frequency of exciting collisions ν_{exc}, the ionization frequency ν_{ion}, the total frequency of electron-atom collisions $\Sigma\nu$ and the energy fraction transferred to the atomon collision δ as functions of the ratio of the electric field strength to the gas pressure E/p (see Figure 5). The values of d we used for determining the frequency of energy loss by electrons in collisions with argon atoms $\nu_u = \delta\cdot\nu_t$ where $\nu_t = \Sigma\,\nu$.

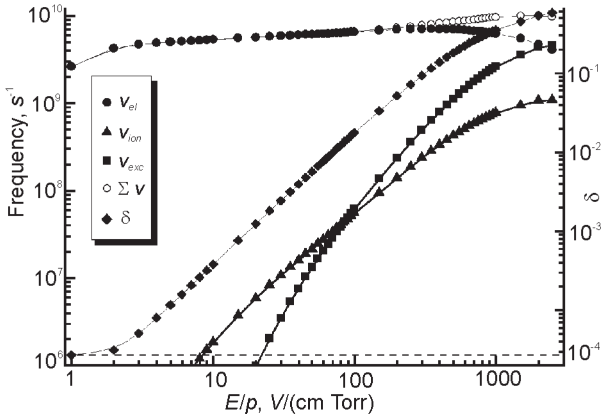

Fig. 5. Dependence of the frequency of elastic collisions of electrons with argon atoms ν_{el} , the total frequency of exciting collisions ν_{exc}, the ionization frequency ν_{ion}, the total frequency of electron-atom collisions $\Sigma\nu$ and the energy fraction transferred to the atom on collision δ on the ratio of the electric field strength to the gas pressure E/p, dashed line is the value of δ for the elastic collisions.

Figure 6 shows the values of ν_u as function of E/p, breakdown curve and the ratio of the breakdown electric field strength to the gas pressure. The dashed line on the figure corresponds to the angular frequency ω for the RF generator frequency f = 13.56 MHz. We have $\nu_u = \omega$ at $E/p \approx 80$ V/(cm Torr) which corresponds to the minimum of the RF breakdown curve.

The energy spectrum of electrons is established at a rate characterized by the frequency of energy loss by the

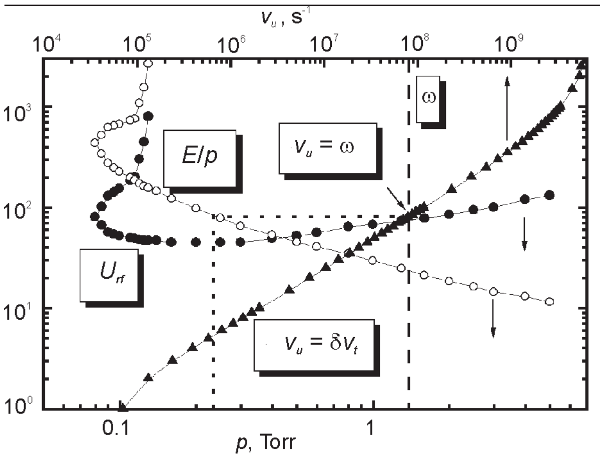

Fig.6. Dependence of the values of н_u on function of E/p, breakdown curve $U_{rf}(p)$ and the ratio of the breakdown electric field strength to the gas pressure $E/p = U_{rf} / pL = f(p)$.

electron in its collisions with atoms $v_u = \delta \cdot v_t$ (for elastic collisions $\delta = 2m/M$, m and M are electron and atom masses respectively). If $\omega >> v_u$, the spectrum has no time to respond to the field oscillations. The spectrum and the mean energy $\bar{\varepsilon}$ remain nearly constant over a cycle and almost coincide with the spectrum and $\bar{\varepsilon}$ that are established in a steady effective field equal to

$$E_{eff} = \frac{E_a}{\sqrt{2}} \frac{v_t}{\sqrt{\omega^2 + v_t^2}} .$$

The ionisation frequency ν_{iRF} in an RF field of amplitude E_a is approximately the same as the ionisation frequency ν_i in a steady field E equal to the effective field

$$v_{iRF}(E_a) = v_i(E_{eff}).$$

In the limiting case of low frequencies $\omega << \nu_u$ the spectrum and the mean energy considerably vary within a cycle. They are strongly modulated and at each moment approximately correspond to the instantaneous field as if it were steady-state. The ionisation frequency ν_{iRF} follows closely the slow field variation and coincides with the ionisation frequency ν_i in a steady field equal to the instantaneous field $\nu_i (E_a \sin(\omega t))$ [4].

Therefore we may use the ionization frequency v_i as a function of the effective electric field E_{eff} only for modellingof the right-hand sides of RF breakdown curve. The ionization frequency v_i as a function of the instantaneous electric field $E_a \cos(wt)$ must be used for the prediction of RF breakdown voltage values to the left of the minimum of the breakdown curve.

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REFERENCES

1. Lisovskiy V.A., Yegorenkov V.D. RF breakdown of low pressure gas and a novel method for electron drift velocity determination in gases// J. Phys. D: Appl. Phys. – 1998. – Vol. 31, №. 23. – P. 3349-3357.
2. Farnsworth H.E. Electronic bombardment of metalsurfaces. // Phys. Rev. – 1925. – Vol. 25, №. 1. – P. 41-57.
3. Baglin V., Bojko J., Grobner O., Henrist B., Hilleret N., Scheuerlein C., Taborelli M. The secondary electron yield of technical materials and its variation with surface treatment//7th European Particle Accelerator Conference.– Vienna (Austria). – 2000, – P. 217.
4. Raizer Y.P., Shneider M.N., Yatsenko N.A. Radio-Frequency Capacitive Discharges//CRC Press, Boca Raton.–1995. – P. 17.

МОДЕЛЮВАННЯ ЗАПАЛЮВАННЯ ВЧ ЄМНІСНОГО РОЗРЯДУ НИЗЬКОГО ТИСКУ

В.О. Лісовський, Ж.–П. Бут

В цій роботі подано результати теоретичного дослідження пробою газу в ВЧ полі. Приведено теоретичні криві запалення ВЧ ємнісного розряду низького тиску в аргоні між плоскими паралельними електродами. Подано аналітичні формули для коефіцієнтів переносу електронів в аргоні, які було отримано методом числового аналізу рівняння Больцмана. Розв'язано рівняння Больцмана для аргону та отримали частоти пружних та непружних зіткнень електронів з атомами аргону, частину енергії, яка передається атому при одному зіткненні δ як функцію співвідношення напруги електричного поля до тиску газу E/p, частоту втрати енергії електронами при зіткненні з атомами аргону v_u. Знайдено, що мінімуму ВЧ кривої запалення відповідає умова $v_u = \omega$. Показано, що частота іонізації v_i, як функція ефективного електричного поля E_{eff} може бути використана лише для моделювання правої гілки ВЧ кривої запалення. Частота іонізації v_i як функція миттєвого електричного поля $E_a\cos(\omega t)$ повинна використовуватися для передбачення величини ВЧ пробійної напруги зліва від мінімуму кривої запалення.

МОДЕЛИРОВАНИЕ ЗАЖИГАНИЯ ВЧ ЕМКОСТНОГО РАЗРЯДА НИЗКОГО ДАВЛЕНИЯ

В.А. Лисовский, Ж.–П. Бут

В настоящей работе представлены результаты теоретического исследования пробоя газа в ВЧ поле. Приведены теоретические кривые зажигания ВЧ разряда низкого давления в аргоне между плоскими параллельными электродами. Представлены аналитические формулы для коэффициентов переноса электронов в аргоне, полученные методом численного анализа уравнения Больцмана. Решено уравнение Больцмана для аргона и определили частоты упругих и неупругих столкновений электронов с атомами аргона, долю энергии, переданной атому при одном столкновении δ как функцию отношения напряженности электрического поля к давлению газа E/p, частоту потери энергии электронами при столкновении с атомами аргона v_u. Обнаружено, что минимуму ВЧ кривой зажигания соответствует условие $v_u = \omega$. Показано, что частота ионизации v_i как функция эффективного электрического поля E_{eff} может быть использована только для моделирования правой ветви ВЧ кривой зажигания. Частота ионизации v_i как функция мгновенного электрического поля $E_a\cos(\omega t)$ должна использоваться для предсказания величин ВЧ пробойного напряжения слева от минимума кривой зажигания.