J. Nano- Electron. Phys.
2 (2010) No2, P. 75-82

PACS numbers: 29.25.Ni, 52.50.Dg, 52.70.Gw, 52.80.Pi

POWER TRANSFER EFFICIENCY IN THE INDUCTIVE RF ION SOURCE

V. Voznyi

Institute of Applied Physics NAS of Ukraine,
58, Petropavlivska, 40030, Sumy, Ukraine
E-mail: vozny@ipflab.sumy.ua

A radio-frequency inductive ion source without magnetic field was analyzed at driving frequency of 27,12 *MHz. Diameter of the source discharge chamber is* 3 *cm, length is* 8 *cm. External electrical parameters of a source such as the coil current and the coil voltage were measured over a power range of* 10-400 *W and gas (argon) pressures ranging from* 0,1 *to* 1 *Pa. The transformer model of an inductive RF discharge was applied to calculate the power transfer efficiency to plasma of the ion source. The power absorbed by plasma is determined to be* 75 % *in the generator power range of* 50-400 *W at the gas pressure of* 0,5 *Pa.*

Keywords: *RF ION SOURCE, ION BEAM, PLASMA, CURRENT DENSITY.*

(Received 19 May 2010, in final form 06 July 2010)

1. INTRODUCTION

Acceleration facilities are one of the main tools for the structure analysis of different materials which use the focused ion beams (FIB). FIB-facilities find wide application in materials science, lithography, micro- and nanotechnology. Radio-frequency (RF) ion sources with a number of advantages, such as long lifetime, simplicity of construction, large ion current (1-100 μA), absence of the heated cathode and purity of the produced plasma, are usually used as the ion sources in FIB-facilities. Reduced brightness of the ion sources of FIB-facilities is equal to 1-30 $A\cdot m^{-2}\cdot rad^{-2}\cdot eV^{-1}$ [1] that provides their spatial resolution of the order of 1 μm [2]. Rapid development of nano-micron technologies requires increase in the resolution of FIB-facilities and decrease in the ion beam diameter less than 100 nm. Calculations show that for the tenfold increase in the spatial resolution of the facility the ion source luminance should be increased by 2-5 orders of magnitude [2]. It is obvious that the increase in the RF source luminance is only possible with the understanding of the physical processes in plasma of the RF source and knowing the source parameters, such as the plasma density, electron collision frequency, power transfer efficiency, etc.

It is known that the RF ion source brightness is proportional to the plasma density formed in the source discharge [3]. Calculations [4] performed on the basis of the global theory of plasma discharge [5, 6] and experimentally confirmed show that plasma density of a cylinder inductive RF source is proportional to the RF power absorbed by discharge. Thus, determination of the RF power transfer efficiency to the source discharge, and so the determination of the absorbed power, is of a great importance. Determination of this parameter is also important from the point of view of the source operation, since low power transfer efficiency leads to poor discharge excitation, production of low-density plasma and overheating of the antenna and tuning elements of the RF source.

In this work we present the investigation results of an inductive RF ion source operating at the frequency of 27,12 MHz without magnetic field. Antenna current and antenna voltage of the ion source were measured subject to the generator power and gas pressure in the discharge chamber. Using the transformer model of an inductive RF discharge [7, 8] we determined the plasma parameters of RF discharge and calculated the coefficient of the RF power transfer efficiency to plasma.

2. TRANSFORMER MODEL OF AN INDUCTIVE RF DISCHARGE

The authors of [7, 8] present the method allowing to determine the internal integral plasma parameters of the discharge by measuring the external parameters of the RF supply circuit, such as antenna current and antenna pressure. Method, named the transformer model of the RF discharge, is based on the following: inductive discharge can be represented as an air transformer where inductive antenna acts as the primary winding, and the RF discharge itself is the secondary one. Magnetic field generated by the currents flowing in the primary winding (antenna) interacts with currents of the secondary winding (plasma current). We have to note that such discharge model can be applied to only the inductive phase of the discharge (H-modes).

Equivalent circuit of the transformer model is represented in Fig. 1a. The Kirchhoff's second law in the complex form for the root-mean-square values of the current and voltage for the antenna and plasma circuits looks like $\dot{V}_1 = (R_0 + j\omega L_0)\dot{I}_1 - j\omega M\dot{I}_2$ and $0 = (R_2 + j\omega(L_2 + L_e))\dot{I}_2 - j\omega M\dot{I}_1$, where I_1 and V_1 are the antenna current and antenna voltage; I_2 and R_2 are the plasma current and active resistance of plasma cylinder.

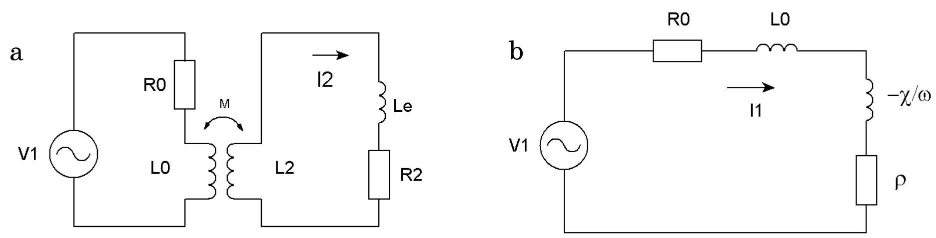

Fig. 1 – *Equivalent circuit of the transformer model of an inductive RF discharge (a) and its sequential equivalent circuit (b)*

Primary coil of the transformer (antenna) contains N windings and has in-ductance L_0 and active resistance R_0. Secondary coil of the transformer (ring discharge) has inductance $L = L_2 + L_e$ and active resistance R_2. Discharge inductance consists of two parts: geometric inductance L_2 caused by the discharge current and inertial inductance L_e attributed to the electron inertia. Inertial inductance L_e follows from the complex nature of plasma conductivity [9]: $\sigma = e^2 n_e / m_e(\nu_{eff} + j\omega)$, where e is the electron charge; m_e is the electron mass; ν_{eff} is the effective frequency of electron collisions; ω is the angular frequency of the generator.

Imaginary part of plasma conductivity defines the inertial inductance of electrons L_e, which can be written as $L_e = R_2/\nu_{eff}$ [7]. Magnetic inductance L_2 is coupled with the inductance L_0 of the primary winding by mutual inductance M: $M = k_L(L_0L_2)^{1/2}$, where k_L is the coupling coefficient between plasma and antenna. Since in the given model plasma represents a single closed loop with current I_2 surrounded by N windings of the antenna, the coupling coefficient is equal to $k_L = (a/b)^2$, where a is the radius of plasma cylinder, b is the radius of antenna coil. In this case the magnetic inductance of the discharge L_2 can be expressed through the antenna inductance L_0, i.e., $L_2 = k_LL_0/N^2$.

Equivalent circuit of the RF discharge (see Fig. 1a) can be transformed into the series circuit (see Fig. 1b). In this case appearance of plasma load is considered as an addition of the equivalent active resistance ρ and the equivalent inductive resistance χ of plasma [8]: $\rho = \omega^2M^2R_2 / z_2^2$ and $\chi = \omega^2M^2(\omega L_2 + \omega L_e) / z_2^2$, where $z_2^2 = R_2^2 + (\omega L_2 + \omega L_e)^2$. Complex resistance Z_1 of the equivalent series circuit and the modulus of complex resistance z_1 are equal to $Z_1 = (R_0 + \rho) + j\omega(L_0 - \chi/\omega)$ and $z_1 = |Z_1| = \left[(R_0 + \rho)^2 + (\omega L_0 - \chi)^2\right]^{1/2}$, respectively.

Root-mean-square values of the RF power P, antenna voltage V_1 and antenna current I_1 are coupled by the relations $V_1 = I_1z_1$ and $P = V_1I_1\cos\varphi$, where φ is the phase shift between the antenna current and voltage.

Active power of the RF generator is distributed between the power P_{ant} induced in antenna and the power P_{abs} absorbed by plasma [6, 8], i.e., $P = P_{ant} + P_{abs} = I_1^2(R_0 + \rho) = R_0I_1^2 + \rho I_1^2$.

Active antenna resistance R_0 is found by measuring the antenna current I_1 and RF power input P without plasma, $R_0 = P/I_1^2$. Inductive antenna resistance ωL_0 is determined measuring the antenna current I_1 and voltage V_1 without plasma. Since $\omega L_0 >> R_0$, then $\omega L_0 = V_1/I_1$.

Equivalent active plasma resistance is equal to $\rho = P/I_1^2 - R_0$, equivalent inductive plasma resistance χ is calculated as $\chi = \omega L_0 - (V_1^2/I_1^2 - P^2/I_1^4)^{1/2}$.

Coefficient η of the RF power transfer efficiency is determined as [6], i.e., $\eta = P_{abs}/P = \rho/(\rho + R_0) = 1 - R_0I_1^2/P$.

3. EXPERIMENTAL EQUIPMENT

General circuit of the RF ion source and description of the experimental setup for measuring source parameters are given in [4, 10]. Inductive ion source has a cylinder quartz discharge chamber with the outer diameter of 30 mm and the length of 80 mm. Spiral antenna (4 windings of a copper tube with the diameter of 4 mm) is wound over the discharge chamber.

RF system consists of the driven generator (27,12 MHz, 40 W), power amplifier “ACOM-1000” (700 W) and matching circuit, which contains the load and resonance variable capacitors. The matching scheme is necessary for the matching of the output amplifier resistance (50 Ohm) with small (1-4 Ohm) active antenna resistance. Measuring device for direct and reflected power (reflectometer “Ronde&Schwarz”) is put between the power amplifier and matching scheme. Adjusting the capacitors of the matching circuit one should obtain the position when level of the reflected (reactive) power is close to zero. In this case direct power is the power P input to the ion source discharge.

Vacuum chamber of the setup is evacuated by the turbo-molecular pump "Leybold-350" which provides the pressure of the order of $5{\cdot}10^{-4}$ Pa.

Measurements of the antenna current I_1 were performed using the amplitude RF ammeter (Fig. 2a) with the integrating Rogowski coil (RC) [11, 12]. The RC (or a current transformer) is a toroidal inductive coil L_1 that surrounds the measured current I_1 with frequency ω. Inductance is shunted by the resistance R_1, and in this case L_1, R_1 and ω should satisfy the condition $R_1 << \omega L_1$. Voltage U is connected with the measured current I_1 by relation $U = (R_1/n)I_1$, where n is the number of coil windings. Sensitivity of the RC, which is equal to $K = R_1/n$, can be increased if the inductance L_1 is wound on a ring ferrite core that allows to decrease a number of loops n. Ferrite ring T225-6 "Micrometals" (57 × 35,6 × 14 мм) with the magnetic permeability of the order of 10 was used in the given RC. The coil consists of 100 single-row windings and has the return loop. To decrease the capacitive coupling between the antenna wire and the inductance L_1 the RC was placed into the copper shield connected with a common earth conductor. A slit in the internal surface of a ring shield was made to provide the magnetic coupling.

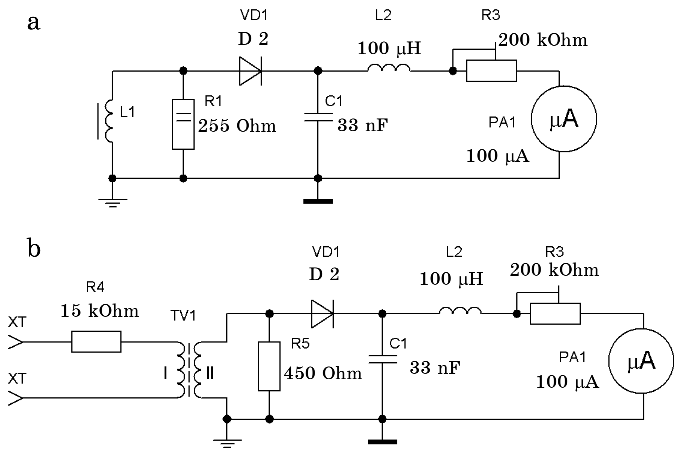

Fig. 2 – Circuit of the amplitude RF ammeter (a) and the RF voltmeter (b)

RF power of the frequency of 27,12 MHz was applied to the dummy active load of 50 Ohm (80 W) while calibrating the RF ammeter. Connection wire of the dummy load was along the RC axis. Feeding the certain power to the load and measuring its voltage (voltmeter V7-17) the current flowing along the RC axis was determined. Resistance R_3 was adjusted to maximum current (100 μA) of the indicator at the measured current of 10 A. Absolute error of measurements of the antenna current was equal to ± 0,2 A.

Measurement of the antenna voltage was carried out using the RF voltmeter (Fig. 2b) with RF transformer [12]. Transformer is made on the ring T225-6 "Micrometals" with the outer diameter of 57 mm and magnetic permeability of the order of 10. Two windings are wound on the opposite sides of the ring, the primary coil contains 40 windings of a multifilament wire in teflon insulation, the secondary coil consists of 10 windings of the same wire. Voltmeter V7-17 was used while calibrating the amplitude RF voltmeter. In this case resistance R_3 was adjusted in such a way that the maximum current (100 μA) of the measuring device corresponded to the measured voltage of 1000 V. Here the absolute error of measurements of the RF voltage was ± 10 V.

4. RESULTS AND DISCUSSION

External electrical parameters of an inductive RF source (antenna current I_1 and antenna voltage V_1) were measured in the RF power range P = 1-400 W. Working gas (argon) pressure in the source discharge chamber varied in the range of 0,1-1 Pa. Spiral antenna of the source contains 4 windings (N = 4), has radius b = 1,8 cm and length l = 3,0 cm. In calculations radius a and length l_2 of a plasma cylinder were equal to a = 1,3 cm and l_2 = 7 cm, respectively.

Active antenna resistance R_0 and inductive antenna resistance ωL_0 were determined without plasma, when ion source was evacuated to the pressure of ~ 10^{-4} Pa. At such pressure plasma in the source was not generated though the RF power was applied to antenna. The active antenna resistance was R_0 = 1,2 ± 0,1 Ohm, the inductive antenna resistance was ωL_0 = 88 ± 4 Ohm.

RF discharge ignited in the source at a certain pressure, and the antenna current I_1 and antenna voltage V_1 were measured subject to the input RF power P. Two different discharge modes are observed in a real RF discharge: the capacitive coupling (E-discharge) dominates at small power, and the inductive coupling (H-discharge) with high plasma density dominates at high power. Measurements of the current I_1 and voltage V_1 were performed only for the inductive discharge phase.

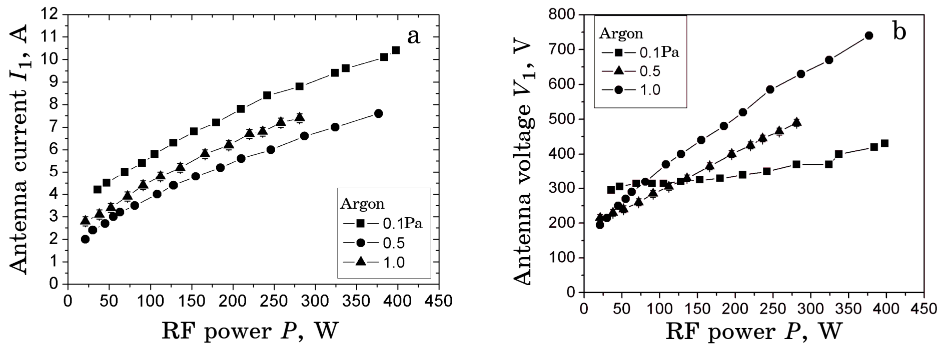

Fig. 3 *– Antenna current I_1 (a) and antenna voltage V_1 (b) versus the RF power P at different argon pressure*

In Fig. 3a and 3b we show the behavior of the current I_1 and voltage V_1 subject to the RF power at different working gas pressure. It is seen that the antenna current I_1 and the antenna voltage V_1 increase with the power.

At 380 W antenna current reaches the value of I_1 = 10 ± 0,2 A at pressure of 0,1 Pa. In this case antenna voltage is V_1 = 420 ±10 V. The phase shift between the current I_1 and voltage V_1 is equal to φ = 85-86° in the inductive discharge phase (P = 50-400 W).

In Fig. 4a we present the dependences of I_1 and V_1 on the argon pressure in the source discharge chamber at 200 W. As seen from this figure, the antenna current I_1 decreases and the antenna voltage V_1 increases with the gas pressure at constant power.

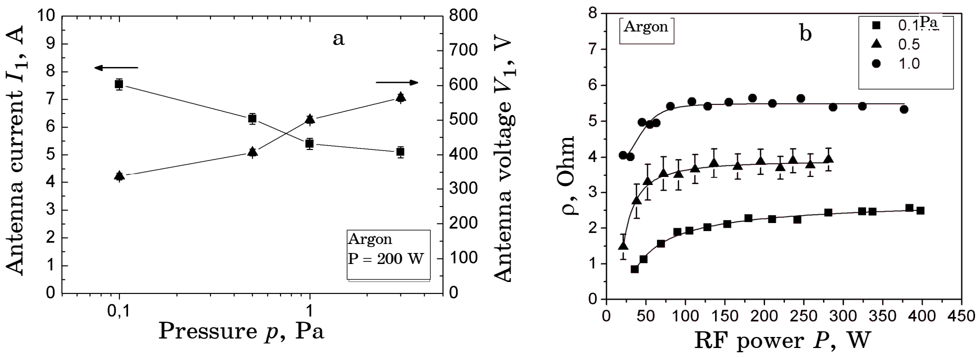

Fig. 4 *– Antenna current I_1 and antenna voltage V_1 versus the argon pressure at P = 200 W (a). Equivalent active plasma resistance ρ versus the RF power at different argon pressure (b)*

Dependence of the equivalent active plasma resistance ρ on the RF power P at different gas pressure is shown in Fig. 4b. There is abrupt increase in the equivalent plasma resistance with the RF power increase from zero to 50-70 W when transition from the capacitive discharge phase to the induc-tive one occurs. In the inductive phase the equivalent plasma resistance ρ increases slowly with the RF power, and at large pressure it almost does not change with the power increase. At fixed power the equivalent resistance ρ increases with the pressure. This implies that power P_{abs} absorbed by the dis-charge increases with the RF power P. In Fig. 4b we present the root-mean-square absolute error ρ determined as the error of indirect measurements (for 0,5 Pa).

Changes in the equivalent inductive plasma resistance χ with the RF power increase are shown in Fig. 5a for the gas pressure of 0,1 and 0,5 Pa. As seen, the inductive plasma resistance χ increases with the RF power.

Modulus of complex resistance z_1 is shown in Fig. 5b subject to the RF power for 0,1 and 0,5 Pa. Modulus of complex resistance z_1 decreases with the RF power increase and increases with the pressure. Since the equivalent resistance ρ increases with power P, the observed decrease in the resistance modulus z_1 with the power increase is caused by the decrease in the total inductive resistance ($\omega L_0 - \chi$) (Fig. 5a). The value of χ has the reversed sign than ωL_0, and increase in χ with RF power leads to the decrease in the modulus of complex resistance z_1. This fact expresses the diamagnetic effect of plasma which is inductively connected with RF antenna [8]. Formed plasma current partly neutralizes the alternating magnetic flux generated by the antenna current, and therefore plasma current flows in the direction opposite the antenna current.

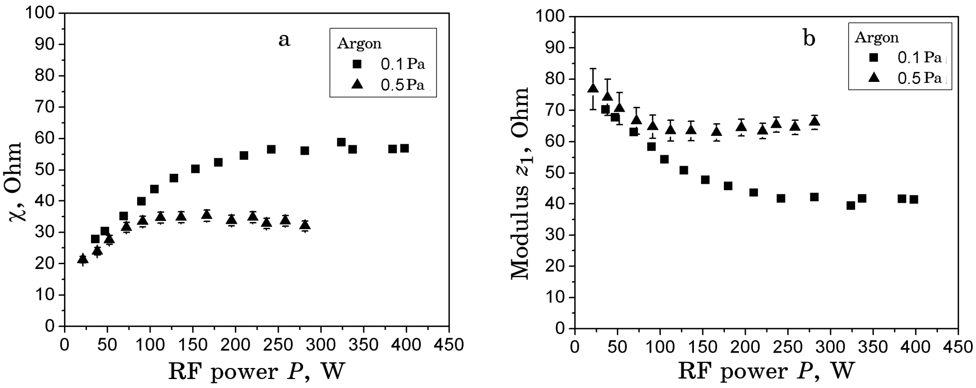

***Fig. 5** – Equivalent inductive plasma resistance χ (a) and modulus of complex resistance z_1 (b) versus the RF power at different argon pressure*

Coefficient η of the power transfer efficiency to plasma is determined from relation (1). Dependence of the coefficient η on the input RF power P is shown in Fig. 6a at different argon pressure.

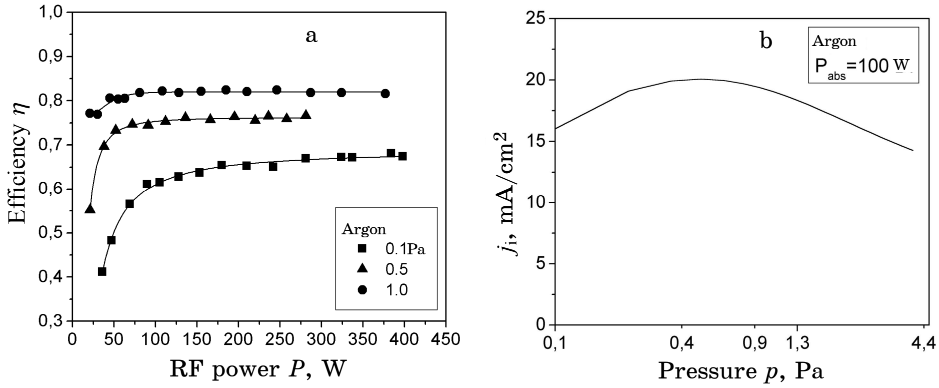

***Fig. 6** – Efficiency coefficient η versus the input power P at different argon pressure (a). Current density j_i of argon ions versus the pressure at the absorbed power P_{abs} = 100 W [4] (b)*

One can see the abrupt increase in the efficiency coefficient in the initial discharge phase, when transition from the capacitive phase to the inductive one occurs in discharge. With further RF power increase, coefficient η have reached the maximum value almost does not change. Efficiency coefficient η increases with pressure. Average values of η are equal to 0,65, 0,75 and 0,82 for pressures 0,1, 0,5 and 1 Pa, respectively. Root-mean-square relative error of η determined as the error of indirect measurements is $\pm$ 10%.

Since efficiency coefficient η increases with pressure, it seems that it is possible to increase η to the value of 0,9 and more by the pressure increase in the source discharge chamber. But in the case of RF ion sources developed to obtain the maximum density of ion current this method cannot be applied. The authors of [4] give the value of current density j_i for argon ions which can be extracted from RF source of the diameter of 3 cm and length of 7 cm. The value of j_i is calculated based on the global model of RF discharge [5]. In accordance with this model the current density j_i is determined by the ion density n_s on the plasma-layer boundary and by the Bohm ion velocity u_B: $j_i = en_su_B$. In Fig. 6b we show dependence of the current density j_i for argon ions on the gas pressure at the absorbed power P_{abs} = 100 W [4]. Current density reaches the maximum value of 20 mA/cm^2 at 0,5 Pa and decreases with pressure increase. Thus, it is seen that pressure increase in the source chamber leads to the decrease in the density of extracted current although it increases the power transfer efficiency to the discharge. As it follows from Fig. 6a the efficiency coefficient is equal to 0,75 ± 0,08 at 0,5 Pa. In order to increase the RF power transfer efficiency up to the value 0,9, it is necessary to decrease the active resistance of the antenna and matching scheme elements by coating them with a thin silver layer (to increase Q-factor of the RF circuit).

5. CONCLUSIONS

Application of the transformer model of an inductive RF discharge gives direct method of determination of the power absorbed by plasma in the RF ion source. Measurements of the antenna current and antenna voltage of the RF source were performed. It was established that power absorbed by source plasma is about 75 ± 10% at the optimal argon pressure of 0,5 Pa. The rest of power is dissipated as thermal loss on RF antenna and matching circuit elements. In order to increase the coefficient of power transfer efficiency it is necessary to increase Q-factor of the ion source circuit.

REFERENCES

1. R. Szymanski, D.N. Jamieson, *Nucl. Instrum. Meth. B* **130,** 80 (1997).
2. D.N. Jamieson, *7th International Conference on Nuclear Microprobe Technology and Applications (ICNMTA-2000)*, art. No. MF-01 (2000).
3. V.I. Miroshnichenko, S.M. Mordyk, V.V. Olshansky, K.N. Stepanov, V.E. Storizhko, B. Sulkio-Cleff, V. Voznyy, *Nucl. Instrum. Meth. B* **201,** 630 (2003).
4. V.I. Voznyy, V.I. Miroshnichenko, S.M. Mordyk, *Problems of Atomic Science and Technology. Series: Plasma Physics* **10** No1, 209 (2005).
5. M.A. Lieberman, A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (New York: Wiley: 1994).
6. J.T. Gudmundsson, M.A. Lieberman, *Plasma Sources Sci. T.* **6,** 540 (1997).
7. R.B. Piejak, V.A. Godyak, B.M. Alexandrovich, *Plasma Sources Sci. T.* **1,** 179 (1992).
8. V.A. Godyak, R.B. Piejak, B.M. Alexandrovich, *Plasma Sources Sci. T.* **3,** 169 (1994).
9. G.G. Lister, Y.-M. Li, V.A. Godyak, *J. Appl. Phys.* **79,** 8993 (1996).
10. V.I. Voznyi, V.I. Miroshnichenko, S.N. Mordyk, V.E. Storizhko, D.P. Shulga, B. Sulkio-Kleff, *VANT. Seriya: Plazmennaya elektronika i novye metody uskoreniya* No4, 284 (2003).
11. Ch.Warton, *Diagnostika plazmy* (M.: Mir: 1967).
12. I.M. El-Fayoumi, I.R. Jones, *Plasma Sources Sci. T.* **6,** 201 (1997).