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MICROWAVE ELECTRONICS

Heating of Electrons in a High-Frequency Inductive Neutral-Loop Discharge

A. V. Arsenin, V. G. Leiman, and V. P. Tarakanov

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Abstract—Two-dimensional self-consistent simulation is used to study collisionless mechanisms for dissipation of energy of the HF field in an inductive discharge developing in the presence of a magnetic field with a neutral loop. The regimes in which the local electron–cyclotron resonance plays the main role in the heating of plasma electrons are demonstrated. The results of numerical simulation are in agreement with published experimental data, thereby making it possible to qualitatively interpret the latter.

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One of the most topical problems of modern microelectronic industry is the development of technologies for producing microelectronic components with a typical size of microstructures of 0.045–0.065 μm on substrates with a diameter of 300–400 mm. This problem involves development of plasma sources for plasma-etching technologies since, normally, a new technological stage of the semiconductor industry necessitates the use of new plasma sources employed for etching of silicon plates. Enhancement of the quality of resulting coatings and of the processing accuracy makes it necessary to decrease the pressure in the working chamber, develop a relatively high spatial homogeneity of the active plasma medium in the vicinity of the plate, and ensure certain energy characteristics of the particles in the plasma. These requirements can be satisfied only through creation of adequate sources of low-temperature low-pressure (10^{-4}–10^{-3} Torr) plasma with a relatively high density (10^{10}–10^{12} cm^{-3}).

Plasma sources based on the HF inductive discharge that develops in the presence of a magnetic field are among the most promising sources for modern plasma technologies. Such sources exhibit a relatively high plasma density (up to 10^{13} cm^{-3}) at working pressures of about 10^{-3} Torr [1].

In this study, we consider a modification of the HF inductive discharge known as the neutral-loop discharge [2]. Such a discharge allows an order-of-magnitude decrease in the working pressure, while the remaining plasma parameters are maintained. This discharge is characterized by the presence of a closed loop on which the magnetic field is zero (neutral loop) in the plane perpendicular to the symmetry axis of the system. In this discharge, a significant amount of plasma can be localized as a ring with a variable diameter. The dynamic control of the plasma parameters allows the implementation of plasma processing with a desired accuracy via the use of variation in the diameter of the plasma ring.

One of the most important criteria for technological application of plasma sources is the efficiency of absorption of the HF field (generated by a feeding antenna) by plasma. Heating of plasma electrons in the HF inductive discharge is related to absorption of the energy of the external HF field by electrons and to transformation of this energy into the energy of the electron chaotic motion. At present, the mechanisms of absorption of the external field energy in HF discharges are classified as collisional (ohmic) and collisionless. In a conventional inductive discharge, the collisionless heating of plasma electrons is caused by the Cerenkov absorption of the HF field in plasma and is manifested at pressures of about 10^{-3} Torr (i.e., in the case when collision rate ν_e is significantly less than the HF field frequency ω) [3]. At the same pressures, the HF inductive neutral-loop discharge is characterized by a higher plasma density. We assume that this circumstance is due to stochastic heating of electrons in the region of the neutral loop [4].

The HF inductive neural-loop discharge emerges in the presence of a nonuniform magnetic field with a complicated configuration in which a local region with zero magnetic field exists simultaneously with the region where the condition for the electron–cyclotron resonance (ECR) is satisfied at the frequency of the HF antenna field. The study of the effect of the magnetic field nonuniformity on the efficiency of the HF-power absorption in the inductive discharge is an important

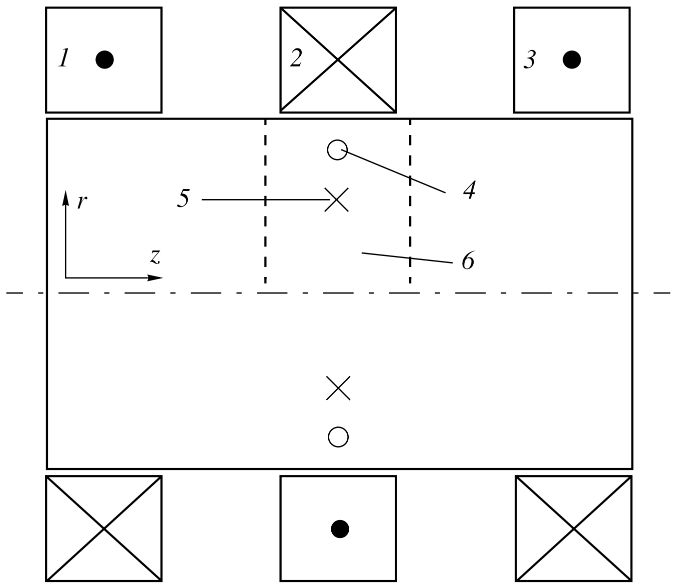

Fig. 1. Diagram of the plasma source: (*1–3*) magnetic coils; (*4*) an HF antenna; (*5*) the position of a neutral loop; and (*6*) the calculation region, bounded by the dashed line.

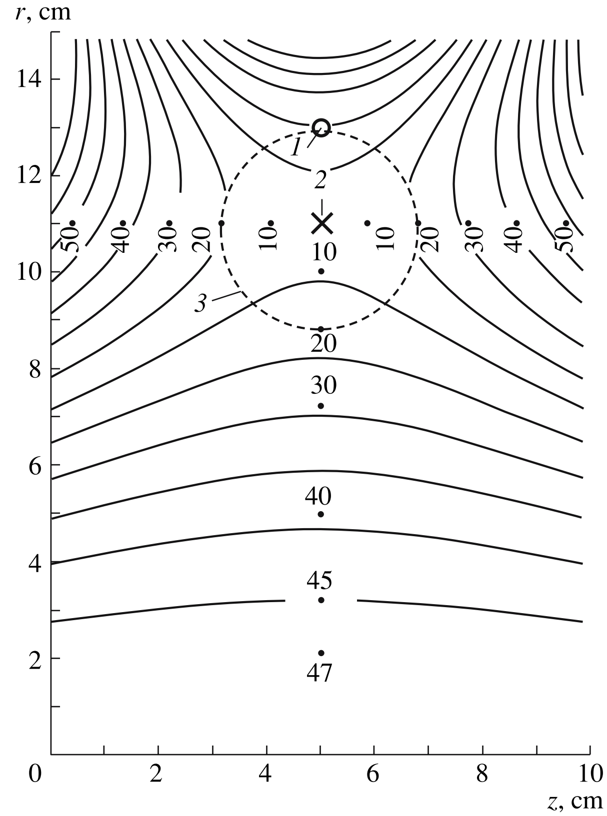

Fig. 2. Magnetic-field configuration in the (*r*, *z*) plane: (*1*) the HF antenna, (*2*) the position of the neutral loop, and (*3*) the loop of the magnetostatic field (B = 20 G). The figures on the curves indicate the magnitude of the magnetic induction (in G) at the corresponding points.

problem since variations in the magnetic field intensity and configuration often affect the output parameters of plasma sources. The analysis of the HF inductive neutral-loop discharge can facilitate solution of the aforementioned problem.

In this study, we employ numerical simulation to study collisionless mechanisms of dissipation of the HF-field energy in plasma of the HF inductive neutral-loop discharge.

Figures 1 and 2 demonstrate the diagram of a simulated plasma source and the corresponding configuration of the magnetic field. The main elements of the discharge system are three electromagnetic coils, a single-turn HF antenna, and a discharge chamber. The working chamber is a hollow cylinder with closed butt-end surfaces. Inside the chamber, we place an HF antenna that consists of a circle coil with a given radius. The antenna excites the vortex field that is used to ignite and to sustain the discharge. A system of three magnetic coils that forms the desired configuration of the magnetic field with a neutral loop is placed outside the chamber. Being mutually codirectional, the currents in the windings of the end coils are contradirectional with respect to the current in the center coil. Such coils excite a mirror-type magnetic field. In the middle plane perpendicular to the coils' axes, a closed zero magnetic loop is formed. Evidently, such a configuration of magnetic coils allows a variation in the radius of the zero-magnetic-field loop, for example, as a result of a variation in the current of the center coil.

The simulation is based on the KARAT electromagnetic code [5], which uses the particle-in-cell method with allowance for the collisions in accordance with the Monte Carlo technique [6]. The computational procedure of the method is presented in detail in [7]. The simulation problem is solved in the 2.5D approximation under the assumption of axial symmetry. The model takes into account the collective interaction of particles, self-consistent fields, the spatial decay of the antenna HF electric field, the presence of the walls of the working chamber, and the electron ionization of atoms of the working gas.

The sizes of the simulated area are as follows: the radius of the cylindrical discharge chamber is $r = 15$ cm and its length is $z = 10$ cm. The numbers of mesh points are $N_r = 201$ along the r coordinate and $N_z = 135$ along the z coordinate. The number of particles (ions and electrons) involved in the calculations ranges from 200000 to 300000, so that 30 to 50 particles correspond to each plasma cell. The radius of the antenna coil is $r_a = 13$ cm. The radius of the neutral loop is $r_n = 11$ cm. The discharge chamber is filled with argon at a pressure of $P = 3.3$ mTorr. Initial plasma with the concentration

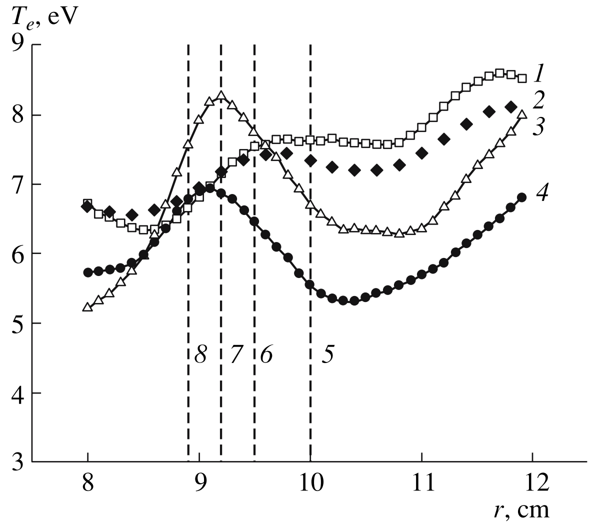

Fig. 3. Radial distributions of the electron temperature for various combinations of pressures and frequencies obtained via numerical simulation: (*1*) $\omega/2\pi$ = 27 MHz and P = 6.6 mTorr, (*2*) $\omega/2\pi$ = 40 MHz and P = 3.3 mTorr, (*3*) $\omega/2\pi$ = 48 MHz and P = 3.3 mTorr, and (*4*) $\omega/2\pi$ = 54 MHz and P = 3.3 mTorr. The dashed lines show the radii for which the ECR condition is satisfied at (*5*) 27, (*6*) 40, (*7*) 48, and (*8*) 54 MHz. The neutral-loop radius is r_n = 11 cm.

$n_i = n_e = 10^8$ cm^{-3} fills the region in the vicinity of the zero-magnetic-field loop rather than the whole discharge chamber. The simulation is performed for several frequencies of the HF current: $\omega/2\pi$ = 27, 40, 48, and 54 MHz.

Most of the experimental data for the spatial distribution of the electron temperature in plasma of the HF inductive neutral-loop discharge indicate that the distribution of electron temperature T_e along the radius in the neutral-loop plane exhibits a single maximum, which coincides with the location of the neutral loop [8]. These data corroborate the theoretical prediction that the discharge efficiency in the collisionless mode is determined by the stochastic acceleration of electrons in the region of the neutral loop.

The results of the simulation show that, when the condition $\nu_e/\omega \ll 1$ is satisfied and the plasma density is such that the Coulomb collisions can be disregarded, the HF inductive neutral-loop discharge is transformed into a regime that is characterized by a shift of the temperature maximum relative to the neutral loop. In this case, the position of the maximum coincides with the region in which the ECR condition is satisfied at the frequency of the external HF field. Figure 3 shows the dependence of the electron temperature on the distance from the axis of the discharge chamber in the plane of the neutral loop for several frequencies of the HF field (27, 40, 48, and 54 MHz). For frequencies of 40, 48, and 54 MHz, the position of maximum T_e on these distribution curves coincides with the region of the currents that satisfy the ECR condition at the frequency of the external HF field (i.e., with the region of the local ECR). The coincidence of the location of the temperature maximum and the ECR region allows the assumption that the ECR heating is realized in this region. For a frequency of 27 MHz and a pressure of 6.6 mTorr, we have $\nu_e/\omega \approx 1$, so that curve $T_e(r)$ does not exhibit a maximum in the region where the ECR condition is satisfied.

Recently, the ECR effect on the parameters of the HF inductive discharge has been doubted. However, the experimental results on the HF inductive discharge in the presence of the magnetic field that is in resonance with the external HF field show that, at a pressure of no higher than 5 mTorr and under the conditions when the Coulomb collisions can be disregarded, such a discharge is characterized by an increase in the electron temperature relative to the discharges realized in the absence of the magnetic field and in the presence of a nonresonant magnetic field [9, 10]. Indirect supporting evidence can be found in theoretical study [3], where an unexpectedly high efficiency is demonstrated for plasma sources based on the HF inductive discharge in the presence of weak magnetic fields that satisfy the ECR condition at the frequency of the external HF field.

The experimental validation of the results obtained by means of numerical simulation can be found in [11]. In that experiment, a distinctive feature that determines the difference between the experimental data on the electron temperature is a relatively high (1 kW) power of the HF oscillator, a property that makes it possible to effectively heat electrons in the region of the local ECR in spite of the decay of the external HF field. (Note that the ECR region is far from the field-decay region.) In the simulation, the field decay is relatively weak owing to a relatively low plasma density.

Thus, the observed increase in the electron temperature in the HF inductive neutral-loop discharge in the region where the ECR condition is satisfied confirms that electron heating can be attributed to both the stochastic mechanism and the local ECR heating.

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