LOW-TEMPERATURE PLASMA

Ion Flows from a Beam–Plasma Discharge

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Abstract—The results of measurements of the energy distribution function of ions escaping from a beam–plasma discharge are compared with the data from probe measurements in the discharge region. It is shown that, on the discharge axis, there is a region with a higher degree of ionization, whose position depends on the external parameters, in particular, on the gas pressure. The mean energy of the ions that leave the plasma from the outside of this region is determined by the potential of the plasma column. Inside the region with a higher degree of ionization, there is an additional mechanism for ion acceleration; as a result, the energy of the ions that leave the plasma from this region is higher than the energy of the electrostatically accelerated ions by a factor of 1.5 to 5. The results obtained show promise for creating a plasma-processing reactor with controlled ion parameters for the purposes of treating materials for microelectronics.

1. INTRODUCTION

In order to optimize the treatment of materials in plasma-processing reactors operating at low gas pressures, it is very important to control the parameters of the ions bombarding the processed material. Thus, in devices for the ion etching of semiconductor materials in an rf discharge plasma, the ion energy distribution function (IEDF) and the angular distribution of the ions bombarding the material’s surface critically affect the rate of etching and the degree of its anisotropy [1]. In order for the structure of films deposited on microelectronics materials to be highly uniform, it is very important to control the energy of the bombarding particles. Control over the parameters of the IEDF (e.g., the mean ion energy and the IEDF width) allows one to selectively affect the physical and chemical processes at a material surface; this is especially important for applications associated with the modification of surfaces [2]. Methods for controlling the shape of the IEDF have been mainly studied for plasma-processing reactors based on rf discharges. It has been shown that it can be controlled, e.g., by applying an rf bias voltage directly to the substrate [3] or by using an auxiliary electron source (either an additional discharge [4–6] or a thermal-cathode gun [7]) to inject electrons into the discharge.

It was shown in [8] that a beam–plasma discharge (BPD) in a low-pressure gas can serve as a source of ions with energies of 10 to 100 eV. In essence, a BPD is a microwave discharge induced by the fields generated in a plasma as a result of the development of a beam instability, so that the BPD parameters are close to those of microwave electron-cyclotron-resonance (ECR) discharges. However, in contrast to an ECR discharge, the BPD does not require high magnetic fields and offers the possibility of generating ion flows with more diverse spatial structures.

In this paper, we compare the results of measurements of the IEDF at the discharge periphery with the data from probe diagnostics of a BPD plasma, namely, with the electron density profile \( N_e(R, L) \), the electron temperature profile \( T_e(R, L) \), and the plasma potential profile \( U_p(R, L) \). We will show that the energy of the ions that drift from the discharge region toward the side wall of the chamber can substantially exceed the energy acquired by the ions in the electrostatic field between the discharge plasma column and the chamber wall.

2. EXPERIMENTAL LAYOUT

A schematic of the experimental device is shown in Fig. 1. The plasma is created in a cylindrical vacuum chamber with a diameter of \( 2R_0 = 0.5 \text{ m} \) and length of \( 0.5 \text{ m} \). The chamber is filled with argon at a pressure of \( 0.006–0.2 \text{ Pa} \). The longitudinal magnetic field with an induction of \( B_0 = 1–5 \text{ mT} \) in the chamber is produced by Helmholtz coils. An axial electron beam is generated by a Pierce-type diode gun with a planar cathode that is placed in a separate chamber connected to the main chamber by a pressure-drop tube. In the electron gun and in the drift region ahead of the plasma chamber, the beam moves in a longitudinal magnetic field with \( H_d = 10 \text{ mT} \) (this value was adjusted experimentally in such a way that the beam current in a high vacuum was maximum). The parameters of an electron beam at the entrance to the plasma chamber are as follows: the energy is \( E_b = 2 \text{ keV} \), the current is \( I_b = 150 \text{ mA} \), and the characteristic diameter is 1–1.5 cm, the duration of the electron-gun supply voltage pulse being \( \tau_p = 150 \text{ ms} \). The electron collector (a graphite
The plasma diagnostics include a planar Langmuir probe in the form of a 3-mm-diameter tantalum disk, whose plane is oriented parallel to the chamber axis. The probe is mounted on a movable rod in order to provide measurements along the discharge axis and in the radial direction. The shape and orientation of the probe are chosen to minimize the effect of the electron beam on the probe characteristic. The electron temperature \( T_e(\mathbf{r}, L) \), plasma potential \( U_p(\mathbf{r}, L) \), and electron plasma density \( N_e(\mathbf{r}, L) \) are calculated by processing the probe characteristic in a standard way \([9]\), namely, from the slope of the curve \( \ln(I_p - I_i) = f(U) \) and from the potential and current of the probe at the inflection point of this curve (here, \( I_p \) is the probe current, \( U \) is the probe potential, and \( I_i \) is the ion current obtained from a linear approximation of the ion part of the probe characteristic). It is well known that, in the presence of an electron beam and oscillations of the plasma potential, the accuracy of determining the plasma parameters from the probe characteristic is rather low; however, it is high enough for our purposes here, because, with the experimentally obtained qualitative dependences, the conclusions drawn in this study are quite justified.

The ion flows are detected by an electrostatic analyzer with a plane deflecting mirror \([10]\). The analyzer is placed near the side wall of the plasma chamber and can be moved along the chamber axis. The ion collimator is oriented along the normal to the chamber axis. The ion analyzer is capable of recording energies in the range of \( 0-100 \) eV with a sensitivity of \( \sim 0.5 \times 10^{-9} \) A/cm\(^2\) and a resolution of \( \Delta W/W_0 = 0.12 \). As an analyzing voltage pulse, we use a 50-ms triangular pulse whose peak coincides with the center of the beam current pulse.

The current to the analyzer’s collector is equal to

\[
I_a = S(\Delta\theta/\Theta_0) J_0 \int_0^\infty f_i(W) A(W) dW
\]

where \( J_0 \) is the total ion current density in the plane of the input window, \( S \) is the area of the receiving window of the analyzer, \( f_i(W) \) is the IEDF (according to the measurement results of \([8]\), this function can be assumed to be isotropic), \( A(W) \) is the spread function, and \( \Delta\theta/\Theta_0 \) is the ratio of the solid angle of the input collimator to the total solid angle of the ion flow arriving at the collimator.

Hence, from the experimental data, we obtain

\[ f_i(W) = \text{const} U(W)/R_i W, \]

where \( U \) is the measured voltage and \( R_i \) is the load resistance of the analyzer’s collector.

The synchronization of the temporal processes is performed with the help of an automatic control system, which is also used to record the time dependences of the current to the analyzer’s collector, the probe voltage and current, and other experimental parameters (such as the beam current and voltage, the gas pressure, and the magnetic field in the chamber). The system is based on a Labcard LC-1250 interface and consists of (i) a 12-bit analog-to-digital converter with a 16-channel multiplex and (ii) a digital output channel, which is used to generate the necessary locking signals. The software package developed for the system ensures the synchronous recording of three “fast” temporal processes, the storage of information on the experimental regime, processing of the data from the energy analyzer (the averaging over the given number of data samples, etc.)