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The influence of oxygen ratio on the plasma parameters of argon RF inductively coupled discharge

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ABSTRACT

In this paper, the RF-coupled plasma characteristics of argon and oxygen mixed gases were analyzed by emission spectra and Langmuir single probes. The experimental pressure was kept at 0.63 Pa, and the electron temperature and electron density were measured by Boltzmann curve method and Langmuir single probe respectively under different oxygen ratio. The results demonstrate that increasing the oxygen content reduces the plasma electron density, and the plasma will change from E mode to H mode when the discharge power increase from 350 W to 400 W if the discharge gas is pure argon or oxygen ratio is low, but the plasma is in a single E-mode at relatively high oxygen ratios. When the power reaches 450 W, the plasma becomes unstable and the state of plasma will change no matter what mode it is (H mode or E mode). In addition, as the oxygen ratio increases, there is a good agreement between the plasma electron density and the argon 738.74 nm line intensity. However, the electron temperature will decrease in H mode.

1. Introduction

Reactive plasmas can produce chemically active species, and plasmas are not only widely used in material research such as surface modification and surface processing, but also in the area such as environment, medical, energy, bio, military as well as high energy density physics research. Plasma processing technology plays a very important role in the global manufacturing industry [1]. Especially in the very large scale integrated circuit manufacturing process, nearly one-third of the process is done by means of plasma processing technology, such as plasma film deposition, plasma etching, and plasma de-gluing [2–4]. The use of these plasma technology to create a special structure and special properties of the material, is the use of other processing technology can not be achieved. However, the improvement of these processes is not only a technical problem, but more importantly, to deepen the study of some complex physical problems involved in the plasma processing. These physical problems include how to obtain a large area of high density uniform plasma under low pressure discharge conditions; how to obtain a stable electronegativity plasma; under what conditions can the optimum etch rate be obtained and so on. To solve these problems, we need to study the plasma generation and control process, such as the external discharge parameters (power source output power, frequency, discharge pressure, working gas type and discharge mode, etc.) on the regulation of plasma parameters. In this study, we used Langmuir probe and emission spectra to diagnose the argon RF induction coupled discharge plasma parameters at different oxygen ratios [5–7]. By changing the proportion of oxygen and adjusting the power, we have studied and discussed the change law.

2. Experimental equipment

The RF inductive coupling plasma source device diagram is shown in Fig. 1. The device is consisted of vacuum chamber, discharge system, vacuum system, cooling water system, gas control system. The reaction chamber is made of a cylindrical quartz glass cylinder which have a height of 30 cm and a diameter of 20 cm, and is used as a dielectric window for power coupling from coil to the plasma and also acted as a sealing chamber. The RF power source is connected by a SY-type RF power source and an SP-II RF adapter (Institute of Microelectronics, Chinese Academy of Sciences). The range of its output power and output frequency are 0 ~ 1 kW and 13.56 MHz respectively, and it is also connected to the discharge chamber high frequency coil through the matching circuit. The vacuum system is made up of 2XZ-2 rotary vane vacuum

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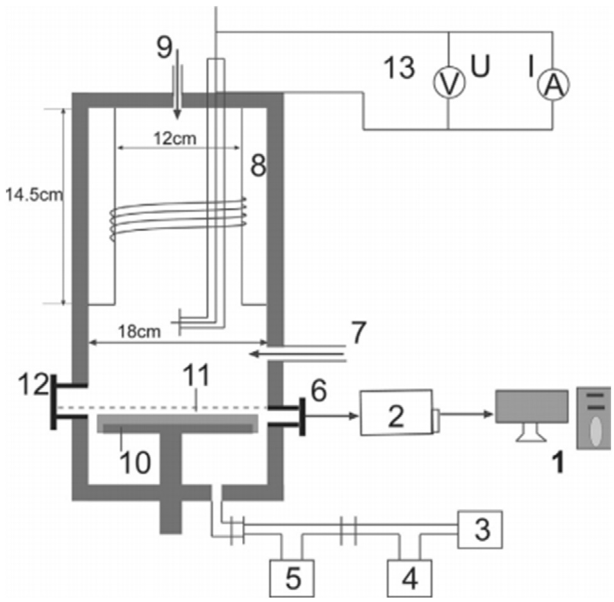

Fig. 1. Schematic diagram of the experimental device.

pump and F-100/110 turbo molecular pump. The mechanical pump can be used as the primary vacuum pump to reduce the pressure of the vacuum chamber to about 4 Pa, and the molecular pump as the secondary vacuum pump. After opening, the vacuum level of the vacuum chamber can be reduced to 6.0×10^{-3} Pa. The air pressure in the chamber is shown by the DL-90 vacuum gauge. The WDS8A combined multifunctional grating spectrometer is used to measure the emission spectrum of Ar gas and the spectrometer has been calibrated before use. The observation window of the discharge chamber and the grating spectrometer are connected by fiber to measure the intensity of the plasma emission spectrum in the chamber. The grating of monochromator is 2400 mm^{-1}, and its blaze wavelength is 350 nm, with spectral measurement range from 200 nm to 800 nm. The plasma electron temperature Te can be obtained from the spectral diagnosis system. In electrostatic probe diagnostic system, a diameter of 1 mm tungsten wire is used as a probe, and the length into discharge chamber is 6.4 mm. A circuit loop is formed by the probe, ammeter and adjustable DC regulator source. From the electron saturation current I_{es} and the electron temperature Te measured from the probe, we can obtain plasma electron density n_e [8,9].

3. Experimental principles

3.1. Principles of spectral diagnosis

The outer electrons of the atoms get the energy from the lower E_1 level to be excited to the higher E_2 level, saying that the atom at this time is in the excited state. When an unstable electron moving in the high energy level back to low energy level, will launch a specific wavelength (λ) of light, thus forming a line in the spectrum. There are:

$$\lambda = \frac{c}{\nu} = \frac{ch}{E_2 - E_1} \tag{1}$$

where c is the speed of light, υ is the frequency, h is the Planck constant. The excited state of the electrons will also be transferred from multiple energy levels back to the original level, which will produce a number of lines, namely, a variety of wavelengths of light. Assuming that the total number of argon atoms in the plasma is N_0, the atoms need to obtain the energy of the excitation energy E, so that the outer electrons of the argon atoms are excited from the ground state to the excited state of the m level and produce a wavelength line, and the number of atoms excited to the m level (E_m) is:

$$N_m = KN_0 e^{-\frac{E_m}{kT}} \tag{2}$$

where K is the statistical constant, k is the Boltzmann constant, and T is the temperature of the plasma.

When the excited electrons return from the excited state to the ground state, the light will be radiated, whose frequency is v and the intensity should be:

$$I = N_m A_{mn} h\nu = KA_{mn} h\nu N_0 e^{-\frac{E_m}{kT}} \tag{3}$$

3.2. Boltzmann curve method [10]

Assuming that the plasma is in steady state, the distribution of the excited state energy particles is the Boltzmann distribution with respect to the upper energy level.

At this time, the intensity of the atomic spectrum satisfies:

$$I = \frac{h\nu}{4\pi} \frac{gA}{Z} N^{-E/kT} \tag{4}$$

here I is the intensity of the atomic line, g is the statistical weight of the upper line, A is the transition probability, v is the frequency of the line, N is the total number of atoms, Z is the partition constant, E is the excitation energy of the line,T For the excitation temperature of the plasma.

From formula (4) we can see that the ratio of the intensity of the two lines of the same atom can be:

$$\frac{I_1}{I_2} = \frac{\nu_1}{\nu_2} \frac{g_1 A_1}{g_2 A_2} \cdot \exp\left[\frac{E_2 - E_1}{kT}\right] \tag{5}$$

The unit of excitation energy E is eV, after the above formula transformed into the common logarithmic form with v replaced by λ and taking $k = 8.618 \times 10^{-5}$eV/K, the temperature of the electron can be attained as:

$$T_e = \frac{5040(E_1 - E_1)}{\mathrm{Log}\frac{A_1 g_1}{A_2 g_2} - \mathrm{Log}\frac{\lambda_1}{\lambda_2} - \mathrm{Log}\frac{I_1}{I_2}} \tag{6}$$

The excitation energy E is found from the spectral table, and the values of g and A are taken from the transition probability table of the National Institute of Standards and Technology (NIST) [11–13], and the spectral intensity I is measured by spectroscopy. It can be seen that the electron temperature can be calculated by measuring the ratio of the intensities of the two lines. The accuracy of this method usually requires the excited energy of two lines have a relatively large gap.

In this study, the relative intensity of the 391.8 nm and 738.74 nm lines is chosen to calculate the electron temperature of the plasma. In addition, from the electron temperature Te and the electron saturation current Ies measured by the probe, we can get the plasma electron density:

$$n_e = \frac{3.7 \times 10^8 Ies}{A\sqrt{kT_e}} \left(cm^{-3}\right) \tag{7}$$

where A is the probe surface area. From the spectral line intensity of