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Using OES to measurement of electron temperature of SF_6/Ar gas mixture of ICP discharges

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Abstract. Optical emission spectroscopy was used to study the properties of the inductively coupled plasma of SF_6/Ar gas mixture. In particular, the effect of RF power supplied to the discharge on the temperature of electrons in the plasma was studied. It was found that the electron temperature gradually decreases with an increase in the RF power. An increase in the RF power from 500 to 750 W leads to a decrease in the electron temperature (T_e) of the plasma by about 1.5 times. A qualitative substantiation of the discovered pattern is given.

1. Introduction
One of the most important tasks in the creation of microelectronic products is to obtain three-dimensional structures with a high aspect ratio on the surface of substrates. Plasma etching is most often used to solve this problem [1]. The main advantages of plasma-chemical etching (PCE) in comparison with liquid etching can be attributed to the high directionality of the process, the absence of restrictions on the size of the etched object, the possibility of complete automation of the process, as well as the efficiency and minimum amount of waste requiring disposal. PCT processes occur at sufficiently low temperatures and pressures, which contributes to improving the quality of manufactured integrated circuits (ICs). However, the requirements for plasma-chemical technologies in terms of the number of permissible defects, selectivity, etching uniformity, etc., are becoming more stringent, which leads to the complication of equipment and the need for strict control of etching processes and, as a consequence, to difficulties in their practical implementation [1-4]. In this regard, it is important not only to understand the influence of technological parameters on the operating parameters of the process, such as the etching rate, etching anisotropy, selectivity, roughness, etc., but also the effect of technological parameters on the properties of the plasma itself. Plasma diagnostics includes many methods that allow you to determine the parameters of the plasma. One of the widespread methods for diagnosing low-pressure gas discharge plasma is the method of optical emission spectroscopy. OES can be used to estimate the temperature of plasma electrons, electron density, etc., without introducing perturbations into the system under study [5-7]. In this work, we have studied the effect of ICP RF power on the electron temperature in the plasma of SF_6/Ar gas mixture.

2. Experimental technique

The experiments were carried out on an original created installation of plasma-chemical etching with a high-density source of inductively coupled plasma (figure 1) [8]. The reactor can be divided into two chambers, discharge and reaction. The reaction chamber is equipped with a viewing window made of KU-1 (FS UV) quartz, 35 mm in diameter, mounted on a flange. This window was used as an optical port for measuring plasma emission spectra. The gases used were high-purity sulfur hexafluoride, 99.998 (GOST TU 6-02-1249-83) and high-purity argon, 99.998% (GOST 10157 - 79).

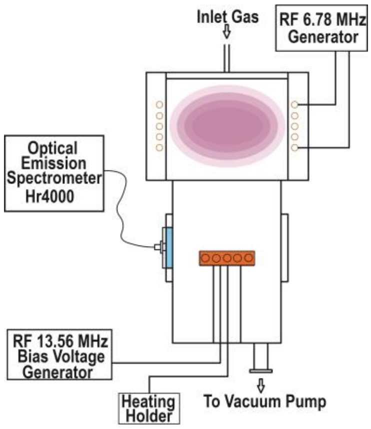

Figure 1. Simplified diagram of the reactor.

The spectra were recorded using OceanOptics HR 4000 spectrometer in the wavelength range of 400 - 825 nm with a resolution of ~ 0.02 nm at a spectrometer entrance slit of 5 μm. The spectrometer was coupled with the setup using a fiber-optic system for transmitting plasma discharge radiation to the entrance slit of the spectrometer (figure1). The spectra were processed using SpectraGryph 1.2.14 software [9].

SF_6/Ar mixture was used as a working gas mixture to study the effect of the ICP RF power on the plasma electron temperature. The RF power supplied to the plasma discharge was varied from 500 to 750 W, and the rate of gas supply to the chamber and the pressure in it were fixed and equal to 7.0 sccm (SF_6), 4.9 sccm (Ar), and 0.5 Pa, respectively.

3. Results and discussions

Figure 2, for example, shows the emission spectrum of SF_6/Ar plasma recorded for the case when the RF power supplied to the discharge was 750 W, the pressure in the chamber was 0.5 Pa, and the bias voltage on the substrate holder was set to level - 50 V. The spectrum is characterized by the presence of a large number of emission bands, the most intense of which are located in the wavelength range of 600–820 nm and are associated with the transitions of Ar and F atoms from one excited state to another (not ground), with a lower energy. The emission spectra measured at other values of the RF power were identical to the spectrum shown in the figure and differed only in the values of the intensities of the emission lines.

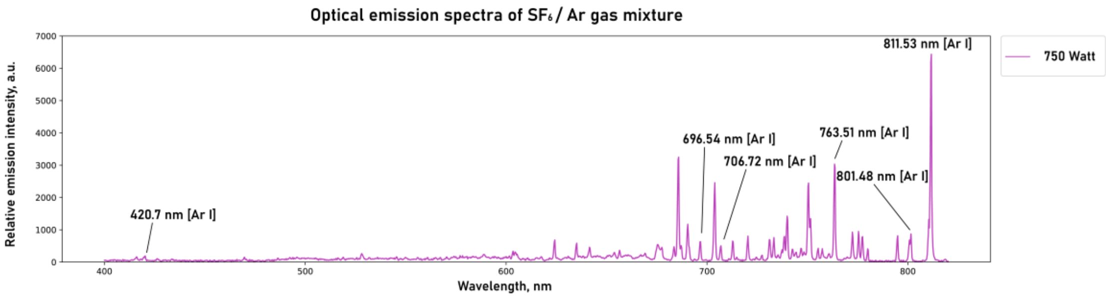

Figure 2. Emission spectrum of SF_6/Ar plasma (W = 750 W, P = 0.5 Pa).

In the approximation of local thermodynamic equilibrium, when the population of excited levels is described by the Boltzmann distribution, the electron temperature can be determined by the method of relative spectral line intensities [10–15]:

$$k_B T = \frac{E_2 - E_1}{\ln\left(\frac{I_1}{I_2}\right) - \ln\left(\frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1}\right)} \quad (1)$$

where λ_1 and λ_2 are the wavelengths of two spectral emission lines corresponding to transitions from two different excited states to the same lower level, I_1 and I_2 are the intensities of these lines, and g_1 and g_2 are the statistical weights of the excited levels.The accuracy of the electron temperature estimate from expression (1) strongly depends on the difference between the energies E1 and E2 of the excited levels and increases with increasing $\Delta E = E_2 – E_1$ and, to a lesser extent, depends on the accuracy of the transition probabilities A_1 and A_2.Therefore, when choosing a pair of lines for calculating the electron temperature, it is reasonable to choose those lines for which the difference in the energies of the upper excited states will be large enough. In addition, the accuracy of calculations can be increased by using several pairs of lines with subsequent averaging of the $k_B T$ values obtained for each pair.In particular, in this work, the following six argon lines were used: 420.07 nm, 696.54 nm, 706.72 nm, 763.51 nm, 801.48 nm and 811.53 nm. The characteristics of the listed lines (configurations of the lower and upper levels, wavelength, energy of the upper level, statistical weight and transition probability) are given in table 1. The necessary information was taken from the NIST database.

Table 1. Parameters of the spectral lines of argon used to estimate the electron temperature.

Configuration		λ_i (nm)	Ei (cm^{-1})	g_i	A_i ($10^6 s^{-1}$)
Lower level	*Upper level*				
$3s^2 3p^5(^{2P^\circ}{}_{3/2})4s{:}^2[3/2]^\circ 2$	$3s^2 3p^5(^{2P^\circ}{}_{3/2})5p{:}^2[5/2]3$	420.07	116942.7542	7	0.97
	$3s^2 3p^5(^{2P^\circ}{}_{1/2})4p{:}^2[1/2]1$	696.54	107496.4166	3	6.4
	$3s^2 3p^5(^{2P^\circ}{}_{1/2})4p{:}^2[3/2]2$	706.72	107289.7001	5	3.8
	$3s^2 3p^5(^{2P^\circ}{}_{3/2})4p{:}^2[3/2]2$	763.51	106237.5518	5	24.5
	$3s^2 3p^5(^{2P^\circ}{}_{3/2})4p{:}^2[5/2]2$	801.48	105617.2700	5	9.3
	$3s^2 3p^5(^{2P^\circ}{}_{3/2})4p{:}^2[5/2]3$	811.53	105462.7596	7	33

It can be seen from table 2, such combinations of pairs of lines (5 pairs) were chosen for which the condition $\Delta E > 1$ eV was satisfied. The results of calculating the electron temperature in SF_6/Ar plasma for various values of the RF power supplied to the discharge for each combination of line pairs are given in table 3. Figure 3 shows the dependence of the averaged values of the electron temperature on the RF power value.

Table 2. Combinations of ratios of the integral area of argon lines and the corresponding differences $\Delta E = E_2 – E_1$.

n	Combination of lines	ΔE (eV)
1	696.54/420.07	1.171
2	706.72/420.07	1.197
3	763.51/420.07	1.327
4	801.48/420.07	1.404
5	811.53/420.07	1.423

Table 3. Results of calculations of electron temperature at different RF power of ICP.

Exp. №1: W = 500 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	459.6	420.07	160.4	2.26

706.72	369.6			3.67
763.51	2291			3.65
801.48	972.3			2.68
811.53	5171			2.36
Exp. №2: W = 550 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	510.9	420.07	159.9	1.87
706.72	412.9			2.72
763.51	2568			2.75
801.48	1058			2.30
811.53	6233			1.79
Exp. №3: W = 600 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	563.2	420.07	173.7	1.82
706.72	466.5			2.50
763.51	2947			2.48
801.48	1025			2.82
811.53	7081			1.70
Exp. №4: W = 650 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	640.5	420.07	195.7	1.80
706.72	509.6			2.67
763.51	3356			2.43
801.48	1403			2.03
811.53	8139			1.66
Exp. №5: W = 700 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	684.9	420.07	200.2	1.68
706.72	555.8			2.34
763.51	3753			2.09
801.48	1560			1.81
811.53	9050			1.51
Exp. №6: W = 750 W, U = -50 V, P = 0.5 Pa				
λ_1, nm	Integral I_1	λ_2, nm	Integral I_2	T_e, eV
696.54	796	420.07	226.8	1.62
706.72	597.7			2.60
763.51	4132			2.19
801.48	1755			1.83
811.53	10180			1.52

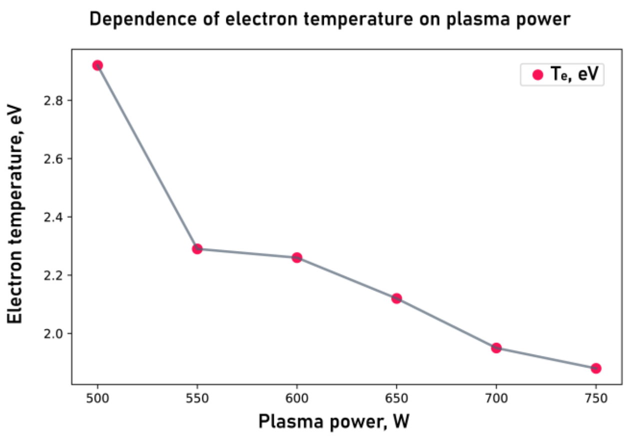

Figure 3. Dependence of the average electron temperature on the RF power of SF_6/Ar ICP.

It can be seen from this figure, an increase in the RF power leads to a monotonic decrease in the electron temperature from 2.92 for W = 500 W to 1.95 for W = 750 W. It can be assumed that the detected gradual decrease in the electron temperature is due to the fact that with an increase in the HF power, the electron density in the plasma increases and, as a consequence, the frequency of electron collisions increases, which means that the probability of energy loss by electrons in various collision mechanisms also increases. This assumption is in good agreement with similar studies by other authors [16,17].

4. Conclusions

Measurements of the emission spectra of SF_6/Ar inductively coupled plasma were carried out at various values of the RF power supplied to the discharge. The method of the ratio of the intensities of spectral lines is used to study the effect of HF power on the temperature of electrons in plasma. It was found that an increase in the RF power leads to a gradual decrease in the electron temperature from 2.92 eV (W = 500 W) to 1.95 eV (W = 750 W). It has been suggested that a decrease in the electron temperature with an increase in RF power is due to the fact that with an increase in RF power, the electron density in the discharge increases, which in turn leads to an increase in the number of collisions of electrons and, accordingly, their energy losses, which is reflected in the value T_e. The high efficiency of the method of optical emission spectroscopy for diagnostics of low-pressure plasma has been demonstrated.

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