Ion Energy Distribution Functions in an Unbalanced Magnetron Sputtering System Developed for a-C Films Deposition[1]

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Abstract – Energy distribution functions (EDF) of argon and carbon ions have been investigated for various working regimes of unbalanced magnetron sputtering system with a graphite target developed for amorphous carbon (a-C) films deposition. It was shown that argon gas pressure (p_{Ar}) and an external magnetic coil current (I_c) were the main parameters affected the measured EDF. Increase of p_{Ar} from 0.1 to 0.4 Pa resulted in the shift of Ar^+ and C^+ EDF maxima toward lower energies and in reduction of high-energy tail of carbon ions EDF, because of thermalization of fast ions in the plasma. Carbon ions peak intensity increased with argon pressure due to higher ionization probability, while argon peak intensity decreased with p_{Ar} in the case of $I_c = 0$ (due to scattering on gas atoms), but increased with pressure in the case of $I_c = 0.2$–0.6 A (due to additional ionization occurred far from the cathode). Both in argon and carbon cases, effect of I_c on EDF was rather complex – on the one hand, the peak intensities tended to decrease with I_c rising due to lower discharge power, on the other hand, the intensities tended to increase due to more effective ionization in the discharge gap at $I_c \neq 0$. As a result, $I_c = 0.2$ and $p_{Ar} = 0.4$ were found to be optimum to maximize Ar^+ and C^+ concentrations in the plasma.

1. Introduction

Magnetron sputtering deposition is one of the well-established and most widely used plasma-assisted PVD methods for producing of various coatings, including hard amorphous carbon (a-C) thin films. The latter ones are known for their excellent tribological properties [1] such as high hardness and low friction coefficient that leads to sufficient increase in wear-resistance and lifetime of coated parts. Normally, usual magnetron sputtering deposition can be applied only for deposition of moderately hard a-C films with a low percentage of tetrahedral bonds. To avoid this, it is necessary to increase plasma density near a substrate that is possible with use of unbalanced magnetron sputtering [2].

According to Thornton structural zone model [3], in the case of sputtering PVD, except a substrate temperature, parameters of ion and atom fluxes impinging a growing film also are very critical for structure of crystalline thin film. This is true for carbon bonding type and resulting properties of amorphous carbon films as well [4]. Although one can find experimental data on plasma characteristics and energy distribution functions (EDF) of ion species for unbalanced magnetrons [5], there is lack of such information in a particular case of unbalanced magnetron sputtering PVD of a-C films at the present time.

Thus, the purpose of the work was to investigate EDF of argon and carbon ions for various working regimes of unbalanced magnetron sputtering system with a graphite target developed for a-C films deposition.

2. Experiment

The unbalanced magnetron sputtering system (Fig. 1) with graphite cathode *1* (diameter of 95 mm, thickness of 6 mm) soldered to water-cooled copper baking plate *2* was developed for the experiments. Arc-shaped magnetic field *7* of 400 Gs was created at the cathode surface by two rings of permanent internal magnets *3* attached to back side of the baking plate. Besides, external electromagnetic coil *4* (3500 turns of copper wire, maximum current of 1 A) was added to create rather high (up to 200 Gs) unbalancing magnetic field *6* far (up to 10 cm) from the cathode at the axis

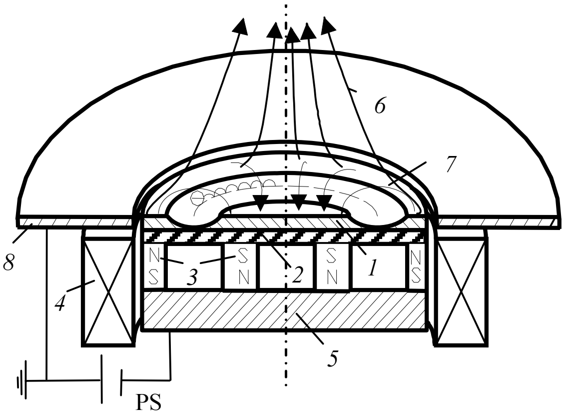

Fig. 1. The simplified scheme of magnetron sputtering system: *1* – sputtered cathode; *2* – baking plate; *3* – two rings of internal permanent magnets; *4* – external electromagnetic coil; *5* – magnetic circuit; *6* – unbalanced lines of magnetic field; *7* – arc-shaped lines of magnetic field; *8* – anode (mounting flange); PS – the power supply of a magnetron

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[1] The work was supported by RFBR Grant No. 07-08-00640.

of the magnetron in order to improve ionization efficiency there. The magnetron was mounted on a flange *8* that was used as an anode.

The flange with magnetron *2* was fixed to the end wall of grounded cylindrical vacuum chamber *1* (diameter of 400 mm, length of 300 mm) (Fig.2).

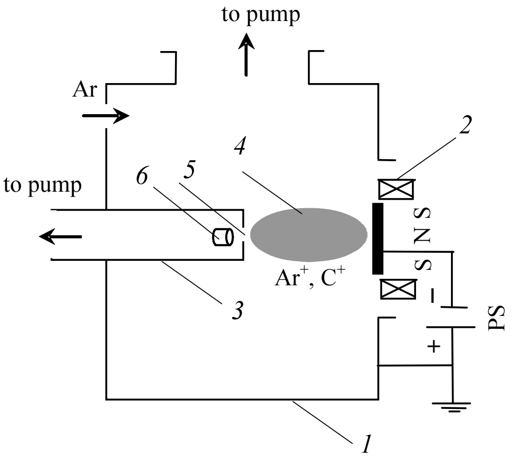

Fig. 2. Experimental setup: *1* – vacuum chamber; *2* – magnetron; *3* – EQP analyzer probe; *4* – gas discharge plasma; *5* – sampling orifice; *6* – extractor; PS – power supply of the magnetron

An electrostatic quadrupole plasma analyzer (EQP standard system by Hyden Analytical, UK) was used for mass-spectrometry of ion species in magnetron discharge plasma *3*. The grounded case of the EQP analyzer probe *4* with sampling orifice *5* of 100 µm in diameter at its end was mounted at the opposite end-wall of the vacuum chamber 10 cm apart the magnetron.

The vacuum chamber was evacuated by a turbomolecular pump, and the EQP analyzer was equipped with a separate turbo pump as well, argon gas could be supplied to the chamber via mass-flow controller. Due to the differential pumping, pressure inside the mass-spectrometer (10^{-7}–10^{-6} Torr) was three orders less than the magnetron discharge pressure (10^{-4}–10^{-3} Torr). Sampling of argon and carbon ions via the orifice was performed by negatively biased EQP extraction electrode *6*.

During the experiments, EDF of argon and carbon ions were measured vs argon gas pressure (p_{Ar} = 0.1–0.4 Pa) and current in the electromagnetic coil (I_c = 0.2–0.6 A) for nearly constant discharge voltage of about U_d = 630–640 V. The discharge current was in the range of I_d = 0.2–0.8 A depending on the p_{Ar} and I_c. The experiments conditions are presented in Table I.

For sampling of argon ions a potential of –300 V was applied to the EQP extractor electrode, and in the case of carbon ions the potential was equal to –500 V. At these voltages, corresponding signals were maximum and stable in the whole range of experimental parameters.

Table I. Magnetron discharge voltage and current vs argon pressure p_{Ar} and external electromagnetic coil current I_c

No.	I_c, A	p_{Ar}, Pa	U_d, V	I_d, A
1	0	0.1	628	0.7
2		0.2	628	0.7
3		0.3	628	0.8
4		0.4	628	0.8
5	0.2	0.1	638	0.7
6		0.2	639	0.7
7		0.3	638	0.7
8		0.4	638	0.7
9	0.4	0.1	642	0.4
10		0.2	641	0.4
11		0.3	641	0.4
12		0.4	641	0.5
13	0.6	0.1	646	0.2
14		0.2	644	0.2
15		0.3	644	0.2
16		0.4	644	0.2

3. Results and discussion

As it follows from Table I, the magnetron discharge parameters mostly were functions of current in the external electromagnetic coil and did not depend on pressure. The fact allows investigating the effect of working gas (argon) pressure on EDF of Ar^+ and C^+ for the magnetron discharge.

Energy distribution functions for argon and carbon vs pressure for various electromagnetic coil currents are presented in Figs. 3 and 4, correspondingly.

First, it is should be noted that quantitative comparison of the Ar^+ and C^+ EDF intensities is useless in our case, since Ar^+ and C^+ ions have been sampled from the plasma at different conditions – as it was noted earlier, maximum of Ar^+ signal was detected at –300 V extractor potential, while maximum C^+ signal was detected at –500 V.

In other words, it is impossible to derive Ar^+/C^+ ratio from the measurements. So, only qualitative analysis of Ar^+ and C^+ EDF and their evolutions with p_{Ar} and I_c are acceptable.

As it can be seen, C^+ EDF covers much wider range. It is connected with the fact, that carbon ions are produced after electron-impact ionization of fast carbon atoms sputtered form the graphite target, while argon ions are produced from the slow Ar gas atoms. As a result, C^+ EDF has its peak at higher energies (1.5–2.5 eV), as well as longer high-energy tail (up to 20 eV) compared to Ar^+ EDF, which peak energy is less than 0.5 eV.

It could be concluded that Ar^+ EDF peak is close to plasma potential (which is positive and around 1 eV for magnetron discharge [5]), while C^+ EDF peak is shifted toward higher energies due to presence of not fully thermalized fast ions.

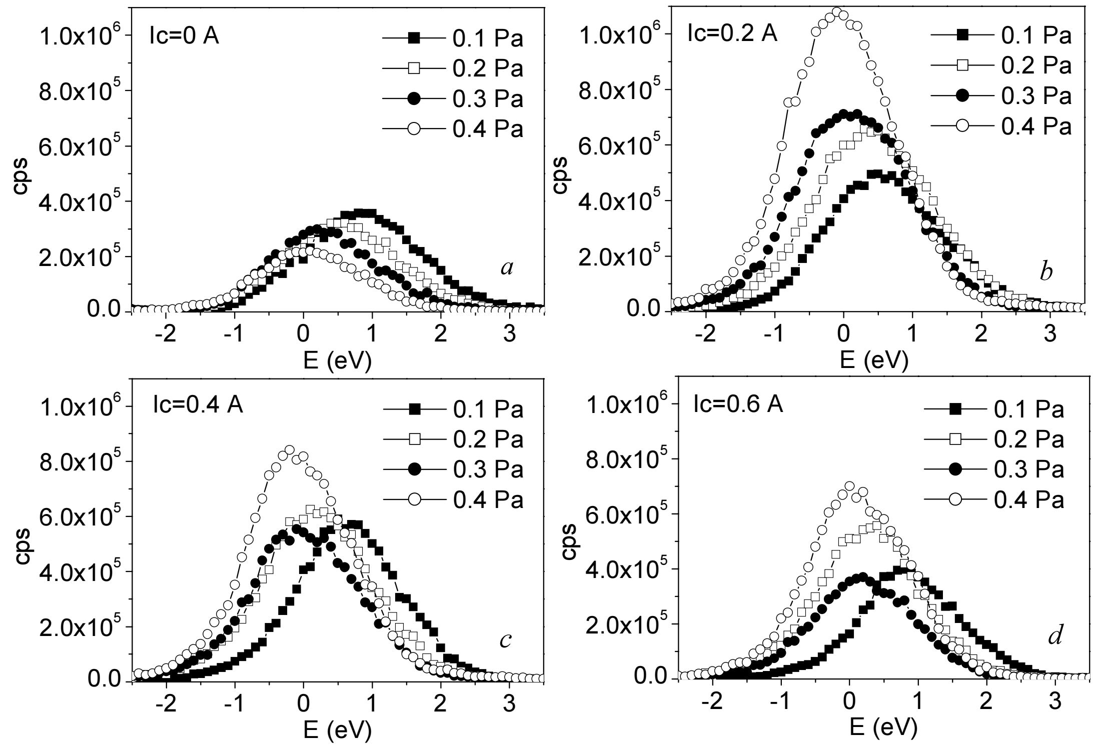

Fig. 3. Energy distribution functions for Ar^+ ions produced at unbalanced magnetron sputtering of the graphite target in Ar atmosphere vs argon pressure for various currents in the unbalanced electromagnetic coil: 0 (*a*); 0.2 (*b*); 0.4 (*c*); 0.6 A (*d*)

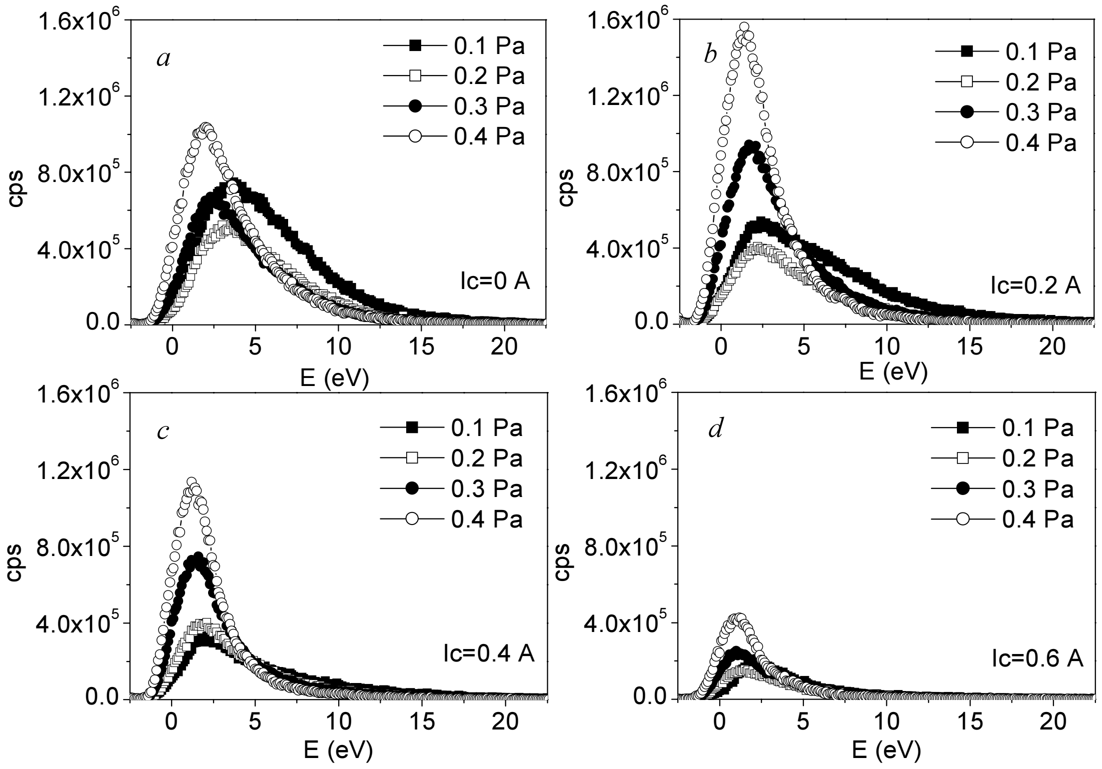

Fig. 4. Energy distribution functions for C^+ ions produced at unbalanced magnetron sputtering of the graphite target in Ar atmosphere vs argon pressure for various currents in the unbalanced electromagnetic coil: 0 (*a*); 0.2 (*b*); 0.4 (*c*); 0.6 A (*d*)

Increase of p_{Ar} from 0.1 to 0.4 Pa results in the shifting of Ar^+ (from 0.5 to 0 eV) and C^+ (from 2.5 to 1.5 eV) EDF maxima toward lower energies and in reduction of high-energy tail of carbon ions EDF. This fact reflects the process of Ar^+ and C^+ ions thermalization in the plasma due to collisions with Ar gas atoms.

Carbon ions EDF both peak and integral intensities increased with p_{Ar} for any I_c. This fact could be explained by higher ionization probability of sputtered C atoms in the discharge gap at higher pressures due to their less velocity caused by more collisional motion. In contrast, argon ions EDF peak and integral intensities decreased with p_{Ar} in the case of $I_c = 0$. Probably, it comes from Ar^+–Ar scattering or charge exchange reactions, which are more probable due to higher cross-sections compared to C^+–C. But for $I_c = 0.2$–0.6, again, Ar^+ EDF intensity increases with pressure as in the case of C^+ EDF. We can conclude here that, besides near-cathode layer, ionization processes take place rather far from it due to unbalancing magnetic field at $I_c \neq 0$. In this case, effect of more active Ar ionization prevails over Ar^+ losses at higher pressure.

Both in argon and carbon cases, effect of I_c on EDF is rather complex. On the one hand, the peak intensities tend to decrease with I_c increase because of lower discharge power (see Table I). On the other hand, the intensities tend to increase due to improved ionization in the discharge gap at higher magnetic field strength. As a result, $I_c = 0.2$ is optimum to maximize Ar^+ and C^+ intensities in the whole pressure range under investigation $p_{\mathrm{Ar}} = 0.1$–0.4 Pa.

Thus, $I_c = 0.2$ and $p_{\mathrm{Ar}} = 0.4$ are optimum parameters to obtain maximum Ar^+ and C^+ concentration in our experiments. Such conditions should be beneficiary for deposition of hard a-C films by the developed unbalanced magnetron that is subject for further research work.

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