Spatial characterization of Ar-Ti plasma in a reactive magnetron system using emission spectroscopy

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The experimental results of the spatial distribution of Ar and Ti excited species in reactive sputtering are presented. The optical measurements were made using a CCD camera and two optical filters, with the transmission bands corresponding to Ar and Ti excited species spectral lines. The discharge operates in two different modes of current variation (square pulse and "symmetric saw tooth"). The experimental results show different distribution and temporal evolution of Ar and Ti excited species. The spatial distribution of argon excited species offers information about electronic density distribution. The spatial and temporal evolution of titanium excited species offer information about dynamic processes that occur at target surface and sputtering rate.

1. Introduction

The reactive sputtering is widely used as deposition technique for nitrides and oxides, etc. The process is non-linear and usually exhibits hysteresis behaviour with respect to the reactive gas flow rate and/or discharge current growth rate [1]. This dynamics depends on a number of different parameters as target material, reactive gas, pumping speed, chamber volume, variation rate of the discharge current intensity, etc.

The chemical reactions of the reactive gas and the target metal either may occur as a surface process (at the cathode or at any other surface covered by the sputtered material) or in the plasma volume. Under these circumstances, the micro and macro parameters of the discharge evolve in time according to the reaction rates of formation and respectively destruction of compounds both on the active surfaces and in the plasma volume. Among these processes, the competition between formation of the compound by physical and chemical absorption of the reactive gas on the cathode surface and its sputtering is the main characteristic of the magnetron discharge in reactive gases [2].

2. Experimental set-up

The measurements were performed in a planar circular magnetron. The target is a titanium disc of 55 mm in diameter. The background pressure is about 10^{-6} Torr and the discharge burns in argon/nitrogen gas mixture. The argon flow rate was kept constant at 14 sccm, while the nitrogen flow rate varied between 0.2 and 0.6 sccm, for a total gas pressure in the range of 10 mTorr. Magnetron discharge was sustained by a dc power supply, which provided a good control of the discharge current intensity. The current intensity was varied in a "saw tooth" mode between 10 and 200 mA or as a square pulse between 20 and 180 mA., The transition time is less than 0.1 s for the square pulse. The discharge current intensity was kept constant after each transition, long enough (40 seconds) so that the new steady state of the discharge is settled. Accordingly, the time evolution of the discharge voltage was measured as parameter for the time evolution of the discharge impedance, which depends on the properties of both cathode surface and plasma volume.

The spatial distribution of Ar and Ti excited species and the dependence of plasma torus area on the discharge current intensity were measured using a CCD camera and two optical filters with transmission band in the range of 700-900 nm and 490-530 nm respectively. The optical system was placed on the cathode axis taking the top view of the plasma volume. Taking into account spatial distribution of the plasma parameters within the plane axial symmetric magnetron discharge, which present a toroidal region of higher plasma density, situated close to the target surface [3], the CCD picture will present projection on the cathode surface of this toroidal region.

3. Results and discussions

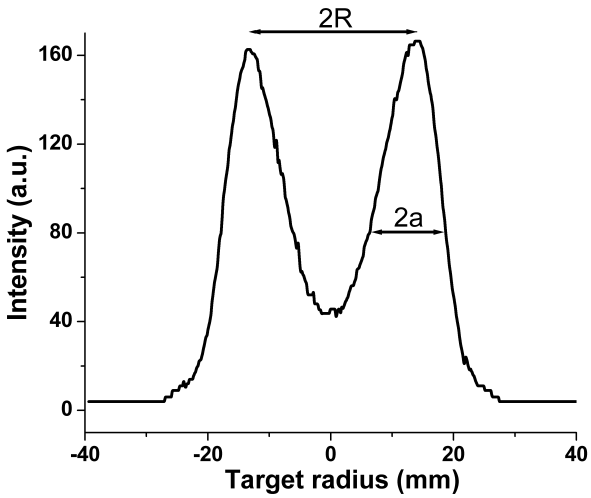
All the results below are discussed for a nitrogen flow rate of 0.4 sccm. Figure 1(a) shows the total plasma light intensity (top view) obtained without any optical filter in the magnetron sputtering system at 180 mA discharge current and 10 mTorr working pressure. In figure 1(b), the corresponding radial distribution of the total light emitted by plasma torus is plotted. This distribution was obtained using the *ImageJ* software (open source software) applied to figure 1(a).

The projection area (top view) of the plasma torus on cathode surface is given by:

$$A = 4\pi Ra \qquad (1)$$

where R and a are the major respectively the minor radius of the plasma torus. The minor radius is obtained as half width of plasma torus intensity distribution (as shown in figure 1(b)).

a)



b)

Fig.1. Top view of the plasma torus (a) and global light intensity distribution (b);

The race-track appears under the bright plasma region due to the high sputtering rate. The distance between the peaks of the radial distribution in figure 1(b) corresponds also to the race-track diameter. The position of the race-track is on the half distance between the two poles of the magnets, where the parallel component of the magnetic field strength to the cathode surface is maximum.

Using the optical filter in the range of 700-900 nm (red filter) the distribution of argon excited species can be obtained, while the optical filter in the range of 490-530 nm (green filter) corresponds to the spectral lines of the titanium excited species. Several operation modes were obtained for different discharge current intensity.

In the "symmetric saw tooth" mode the discharge current was linearly increased and then decreased in time between 10 and 200 mA with 4 mA/s growth rate. In the corresponding voltage – current characteristic (figure 2), one can see the discharge operation mode at increasing and decreasing of the discharge current intensity. Thus, on branch *ab* and *fa* (figure 2), the discharge operates in so-called compound mode. In this operation mode, the compound (TiN) covers the whole target surface and the sputtering rate of the titanium nitride is low. On branch *cde*, (figure 2), the magnetron operates in metallic mode, the race-track surface is metallic and the sputtering rate of titanium is large in this region. On branch *bc* and *ef*, (figure 2), the discharge operates in transitional mode, the race-track surface is partly covered by the compound but metal atoms are sputtered mainly from the metallic region.

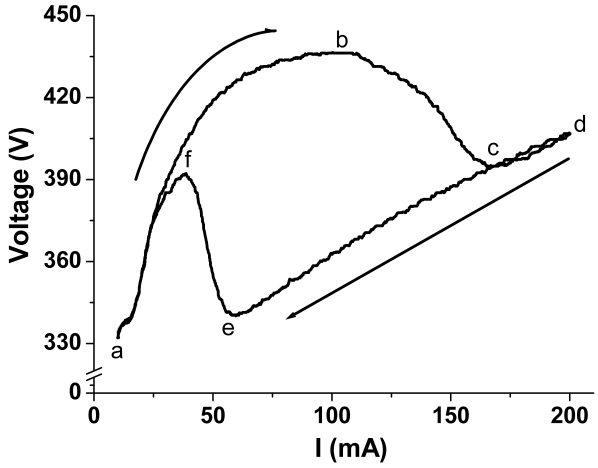


Fig.2. Voltage-current characteristic, Q[Ar]=14 sccm, Q[N_2]=0.4 sccm, $\Delta I/\Delta t$=4 mA/s, p=10 mTorr;

Plasma torus area, calculated using red and green optical filters, is shown in figure 3 versus discharge current intensity.

The plasma torus area obtained with the red filter (corresponding to Ar excited species) increases with the discharge current up to 100 mA, and then trends to be constant. This evolution is strongly related with the evolution of the electron density. The electrons torus expands with the discharge current up to a certain limit, dictated by the magnetic trap geometry.

The spatial distribution of argon excited species is independent by the discharge operation mode related to the nature of the target surface.

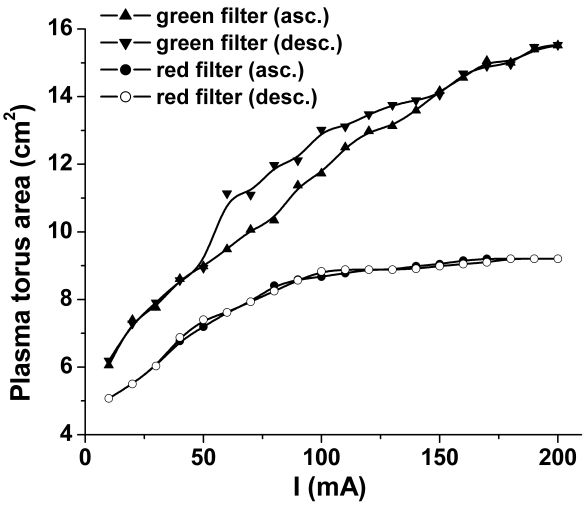


Fig.3. Plasma torus area vs. discharge current intensity, Q[Ar]=14 sccm, Q[N_2]=0.4 sccm, $\Delta I/\Delta t$=4 mA/s, p=10 mTorr;

The plasma torus area obtained using the green filter (corresponding to Ti excited species) increases with an almost constant rate with the discharge current intensity. The number of the excited titanium atoms grows with the sputtered titanium quantity at the target surface, which is proportional with the current discharge. Moreover, the excitation rate of titanium atoms overcomes the excitation rate of the argon atoms [4]. In this case, area of the plasma torus depends on the operation mode. For the same current value, in metallic mode the plasma torus area is larger than that on the compound mode. Moreover, the area of the torus projection given by titanium excited species presents hysteresis effect with respect to the discharge current intensity.

The same kind of measurements was performed by operating the discharge in pulsed current mode. Time evolution of the voltage discharge (figure 4) indicates the main discharge operation modes. In point *a* and on branch *d"e* (I=20 mA), the discharge operates in compound mode and on branch *b'c* (I=180 A), the discharge operates in metallic mode. On branch *abb'* and *cdd'd"* the discharge operates in transitional mode from compound to metallic and reverse [4].

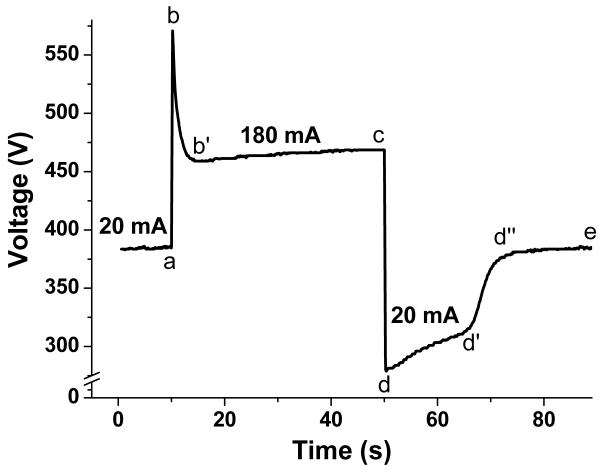


Fig.4. Time evolution of the discharge voltage for a square pulse of current from 20 to 180 mA, Q[Ar]=14 sccm, Q[N_2]=0.4 sccm, p=10 mTorr;

As it can be observed from figure 5, the torus areas of argon and titanium excited species from the discharge are very different. These differences are the consequence of the generation mechanisms of these species [6]. Working gas is argon and in a first approximation, it has an uniform distribution inside the discharge chamber. As a result, the majority of excitation processes of argon atoms takes place in the magnetic trap zone were the electron density is high and their energy is sufficient to produce ionizations and excitations.

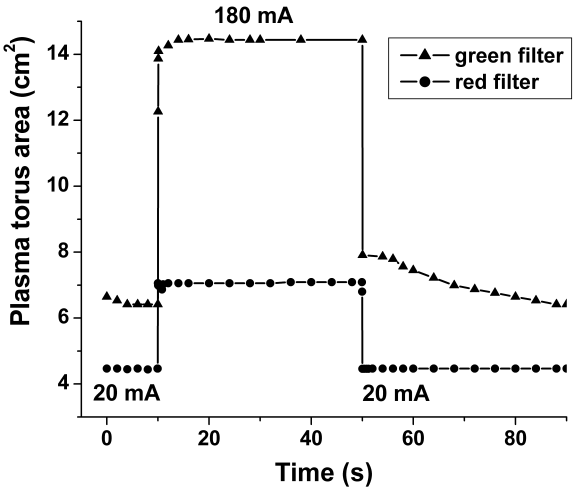


Fig.5.Time evolution of plasma torus area vs. discharge current intensity, Q[Ar]=14 sccm, Q[N_2]=0.4 sccm, p=10 mTorr;

The time evolution of plasma torus corresponding to argon excited species (red filter), is the same with the current pulse. This is mainly due to the fact that the argon density remains relatively

homogenous and the light emitting phenomena take place in a volume, which depends on the spatial distribution of magnetic trap, as shown also in the "symmetric saw tooth" variation mode.

Due to their lower excitation potential than the argon atoms, the excited titanium atoms have a broader volume distribution [7]. Another important characteristic of titanium atoms density is that the distribution is un-homogeneous, depending on the sputtering processes on the target surface, mainly discharge current distribution. In the case of reactive sputtering this un-homogeneity becomes even complicated, depending also on the target surface contamination profile.

Changing the discharge current from 20 to 180 mA, and from 180 to 20 mA the plasma torus area for titanium species presents a transition interval as seen in figure 5. The steady states when discharge operates in metallic mode, respectively compound mode, are reached only after a few seconds of transitory state. The quantities of sputtered titanium and its spatial distribution depend on the current discharge and contamination degree of the target surface.

4. Conclusions

The experimental results show different distribution of Ar and Ti excited species in the discharge volume.

The spatial distribution of the argon excited species is independent by the operation mode of the discharge and is conditioned only by the spatial expansion of the magnetic trap.

Information about dynamic processes that occur at target surface and sputtering rate are obtained from spatial distribution and temporal evolution of titanium excited atoms.

The spatial distribution of the titanium excited species depends on both the contamination degree of the target surface and the discharge current value.

This method can be successfully applied to determinate the spatial distribution of the other excited species if filter's transmission range corresponds with the spectral range of the lines group.

5. Acknowledgements

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6. References

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