ENERGY TRANSFER TO THE WALLS AT LOW PRESSURE PLASMA PROCESSING

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Abstract

From the integral energy influx measured by temperature gradients and the plasma parameters in front of the substrate the contributions of charge carriers and radiation to substrate heating at plasma deposition were calculated. There was found a strong correlation between the influence of the energetic particles and the mass density of the deposited films.
The energy transfer is illustrated for two examples: titanium layer deposition with a hollow cathode arc discharge and sputtering of thin titanium films in a magnetron discharge.

Introduction

Plasma-wall interactions are present in a large variety of plasma chemistry applications such as etching, deposition and surface modification. In these complicated phenomenas the thermal conditions at the substrate surface play a dominant role. The surface temperature T_S influences elementary processes like adsorption, desorption, and diffusion as well as chemical reactions (chemical sputtering, surface film reaction) [1].
The surface temperature is strongly influenced by the internal energy influx due to energetic particle bombardment, exothermic reactions and heat radiation. Especially in the case of thin film deposition the structure and morphology as well as the stoichiometry of the film depend strongly on the thermal conditions at the surface [2]. The surface diffusion of adsorbed atoms can be enhanced, which results in a rearrangement of deposited atoms. In addition, an irradiation of a growing film with low-energy ions results in a modification of its properties [3].
The energy transfer between plasma and solid is a very difficult mechanism. The thermal conditions at the surface must be described by a detailed energy balance, which considers the different heat sources and heat losses and their transfer mechanisms.
Since hollow cathode arc evaporation and magnetron sputtering are common methods for thin film deposition the influence of the plasma must be known in regard to the production of involved species (ions, excited neutrals etc.) as well as concerning the energy influx towards the substrate.

Experiments

The energy influx measurements during titanium deposition have been performed in a hollow cathode arc evaporation device (HCAED) and in a planar magnetron. The plasma of the hollow cathode arc with a high ionization degree has three functions: activation of the particles near the substrate, activation and cleaning of the substrate surface and transformation of solid coating titanium placed in a crucible anode into the vapour phase.
The used magnetron consists of three permanent magnets (0.027 T). Thus, there are two transitions where the current density and the sputtering rate shows a maximum.
The experimental standard conditions were the following:

	HCAED	magnetron
current	130...240 A	15...450 mA
voltage	20...27 V	250...500 V
discharge power	2.5...6.4 kW	40...140 W
substrate voltage	$-80...0\ V$	0 V
gas pressure	0.2 Pa	0.1...1 Pa
Ar gas flow	95 $Pals^{-1}$	40...250 $Pals^{-1}$
deposition rate of titanium	0.1...2 nms^{-1}	0.4...1.2 nms^{-1}
distance anode - substrate	18 cm	5 cm
surface temperature	40...200 $°C$	20...100 $°C$

To vary the energy influx towards the substrates the discharge power and the bias voltage of the substrate have been changed.
The energy flux density J_{in} to the substrate was determined by measuring the temperature gradient along the sample holder or by evaluation of the surface temperature monitored by type-j-thermocouples.
Simultaneously to the measurements of the energy inflow the electrical currents towards the substrate and the plasma parameters in front of the substrate were determined by means of LANGMUIR-probes placed in front of the substrates. The electron densities n_e, the mean energies of the electrons kT_e and the plasma potentials U_{pl} were derived from the numerical second deviation of the probe characteristics. The energy distribution and the relation between the ions in dependence on the discharge power were measured by means of a plasma monitor in case of the HCAED.
Deposition rates and film densities have been obtained by ellipsometry during the titanium deposition on silicon wafers.
A scheme of the experimental setups is given in Fig. 1.

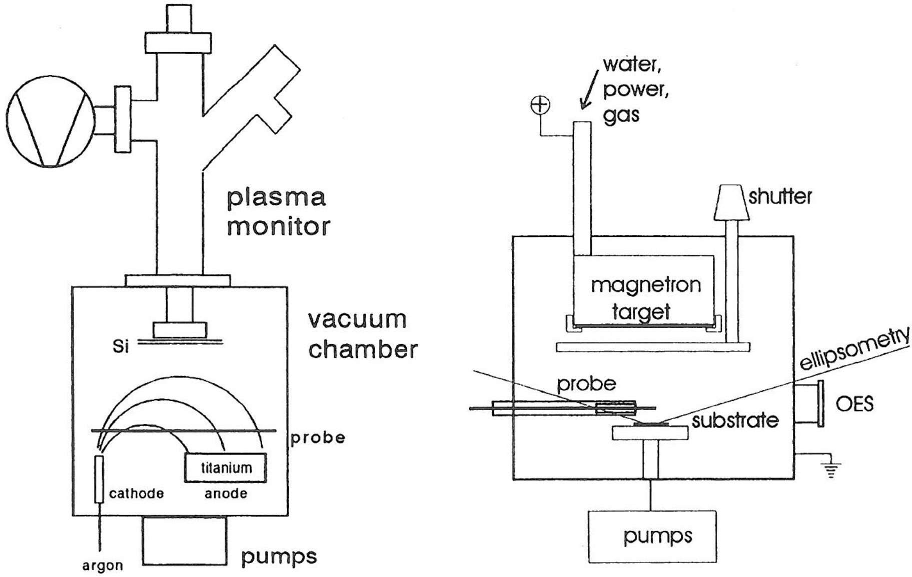


Fig. 1: Experimental set-up, schematic (HCAED, magnetron).

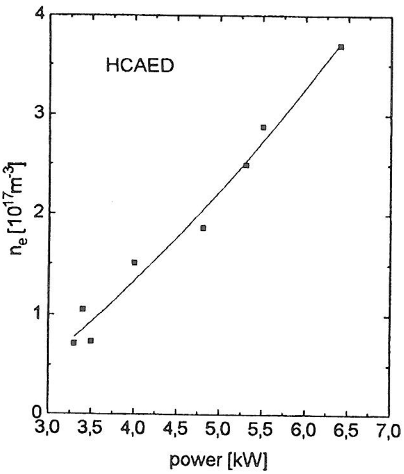
Results and Discussion

The energy inflow to the substrate consits of the heat radiation (especially of the molten titanium in case of HCAED), the energy due to energetic particle bombardement (charge carriers, neutrals) and exothermic reactions (film condensation). The condensation heat was calculated by the deposition rate, the mass density and the specific condensation heat of titanium. This contribution is proportional to the discharge power as the deposition rate, too. However, it is in both cases neglegibly low compared to the other contributions.
The energy flux densities of charged particles (J_e, J_i) are given by the product of the particle flow densities (j_e, j_{ion}) to the substrate and the mean particle energies (E_e, E_{ion}). In case of a MAXWELLian energy distribution the particle flow densities of electrons to a wall which is negatively charged in respect to the plasma are deduced from:

$$j_e = n_e \sqrt{\frac{kT_e}{2\pi m_e}}\, e^{\frac{-eU_{bias}}{kT_e}} . \qquad (1)$$

The electron densities in the substrate regions obtained by probe measurements are proportional to the discharge power in both deposition methods, see Fig. 2. The mean electron energy kT_e at the substrate was estimated to be about 5 eV at HCAED and to be about 2 eV in magnetron sputtering. To reach the surface the electrons have to overcome the bias voltage U_{bias}. Thus the kinetic energy of the electrons E_e arises from the integration over the energy distribution function from U_{bias} up to infinity:

$$E_e = 2kT_e + e_0 U_{bias} . \qquad (2)$$



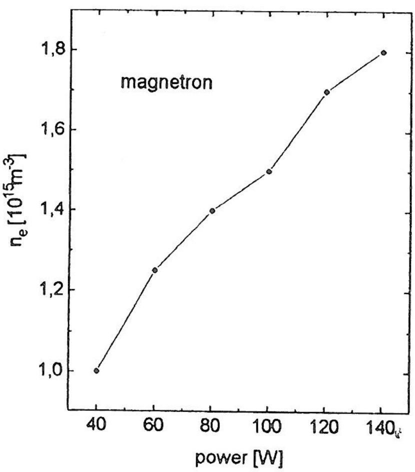


Fig. 2: Electron density vs. discharge power, 0.2 Pa.

The ion current density to the substrate is given by

$$j_{ion} = n_e \sqrt{\frac{kT_e}{m_{ion}}}\, e^{-\frac{1}{2}}. \tag{3}$$

The positive ions are accelerated in the electrical field in front of the substrate and get in addition to their mean thermal energy $\frac{3}{2}kT_{ion}$ a kinetic energy e_0U_{bias}.

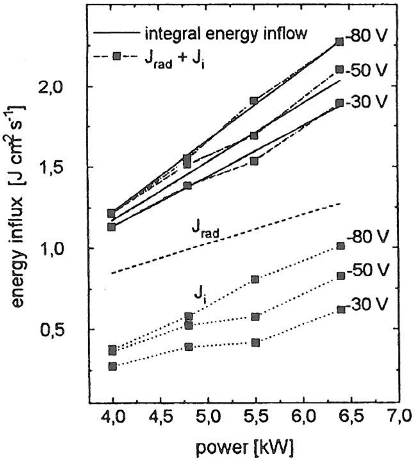
$$E_{ion} = \frac{3}{2}kT_{ion} + e_0U_{bias} \tag{4}$$

The contribution of electrons and ions to the substrate heating depends strongly on the substrate bias voltage which consists of the external substrate voltage U_s and the plasma potential U_{pl}.

At HCAED for $U_s \leq -30\ V$ only the ions determine the contribution of the charge carriers whereas the electrons have to be considered in the case of $U_s \to 0$. Unfortunately, at magnetron sputtering the substrate voltage has not been changed. The radiation J_{rad} of the molten titanium in HCAED depends only on the discharge power and is not influenced by the bias voltage. Therefore this contribution can be seperated by variation of U_s. For all considered substrate voltages the heat radiation is the dominating part for substrate heating, followed by the part of the charge carriers in HCAED deposition. As an example Fig. 3 shows the integral energy inflow and the separation into radiation and influx of ions for $U_s \leq -30\ V$ vs. discharge power.

In magnetron sputtering it has been found that the energy inflow increases with power and pressure and reaches a maximum at a gas pressure of 0.6 Pa connected with a maximum of the plasma density and a maximum of the mass density of the deposited titanium films. Fig. 4 shows the relation between energy influx, power, and pressure. Because of the low positive bias voltage the electrons are dominant.

However, their contribution is relatively low compared to the fast neutrals from the target.



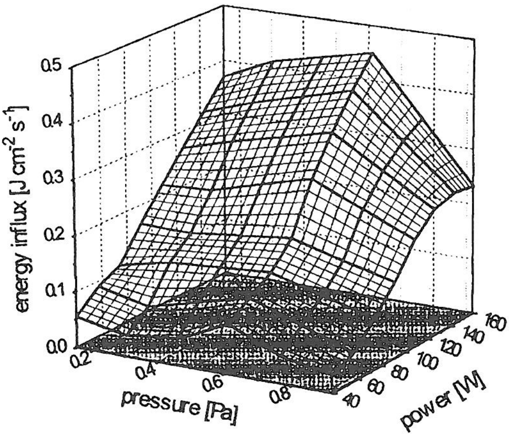


Fig. 3: Integral energy inflow at HCAED and its separation into the contributions of radiation and ions.

Fig. 4: Energy influx at different discharge conditions in magnetron sputtering.

The importance of energetic particles in regard to layer deposition is not only for substrate heating. Moreover, the ions are often the essential component to increase the film quality by ion mixing etc. A relatively small portion of ions may change the properties of a deposited layer in a drastic manner. For instance, an ion irradiation of the growing film influences the acceleration of the nucleation stage, destruction of columnar structure, modification of crystal orientation, and stoichiometric changes. Especially the layer density can be influenced by the ions [3].

The relationship between the ion species in dependence on the discharge power was of special interest which has been measured by energy resolved mass spectrometry in HCAED [4]. The result is plotted in Fig. 5. It is obvious that at low power the Ar ions are dominating species whereas at higher discharge power ($\geq 4.5\ kW$) Ti ions become important. At high power there is a large supply of titanium vapour and because of the greater ionization cross section of titanium compared with argon the metal vapour can be ionized more effective than the inert gas. The variation in the ion composition with discharge power can also be seen in a change of the properties of the deposited films. In the power scale dominated by the Ti ions the mass density of the titanium layers is remarkably higher (Fig. 6).

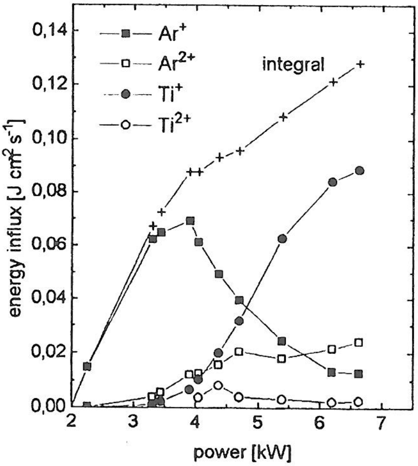


Fig. 5: Energy inflow by the several ion species.

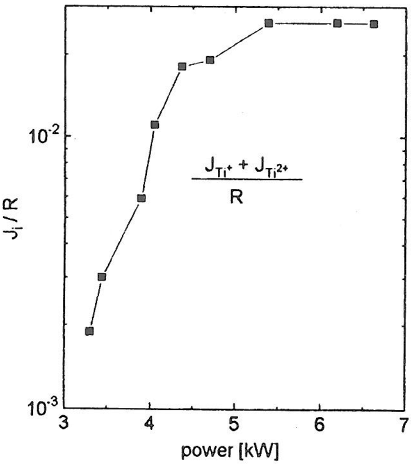


Fig. 6: Relation between energy inflow by Ti ions (J) and deposition rate R.

Conclusions

The measurement of the energy inflow towards substrates during plasma processing is important for thin film deposition.
In HCAED it was found that besides the radiation from the crucible for sufficiently negative substrate voltages ($U_s \leq -30V$) the contribution of the ions to the integral energy inflow is essential. It can be estimated from the parameters of the plasma measured by LANGMUIR-probe in front of the substrate and by plasma monitoring. In magnetron sputtering electrons and sputtered neutrals were determined to be the dominant species causing substrate heating.
Besides the thermal conditions at the substrate surfaces the energy supplied by the energetic particles influences the mass density of the deposited layer material.

References

[1] DEUTSCH,H., KERSTEN,H., RUTSCHER,A.,
Contrib.Plasma Phys. 29(1989)3, 263.

[2] THORNTON,J.A.,
J.Vac.Sci.Technol. 11(1974), 666.

[3] MULLER,K.H.,
Appl.Phys.A 40(1986), 209.

[4] KERSTEN,H., STEFFEN,H., VENDER,D., WAGNER,H.-E.,
Vacuum 46(1995)3, 305.