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ION HEATING PROCESS DURING PLASMA IMMERSION ION IMPLANTATION

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The research on plasma immersion ion implantation has been conducted for a little over ten years. Much is needed to investigate including processing technlogy, plasma sheath dynamics, interaction of plasma and surface, etc. Of the processing methods elavated temperature technique is usually used in PIII to produce a thick modified layer by means of the thermal diffusion. Meanwhile plasma ion heating is more recently developed by Ronghua Wei et al[1]*. Therefore the temeperature is a critical parameter in plasma ion processing. In this paper we prèsent the theoretical model and analysize the effect of imlantation voltage, plasma density, ion mass, etc on the temperature rise.*
KEY WORDS *plasma immersion ion implantation, ion heating, temperature*

1. Introduction

Ion bombardment using plasma immersion method has proven an effective surface modification technique[2,3]. Plasma immersion ion implantation (PIII) can significantly improve the surface properties of the components, such as hardness, friction, wear-resistance and corrosion-resistance of the materials. Meanwhile its biggest advantage is the ability to treat irregularly shaped objects without the necessity of target manipulation. PIII process can be conducted by either at a low temperature (<100°C) or elevated temperature conditions (usually 300°C–500°C). The latter method is preferred for the treatment of the stainless steel because elevated–temperature process increases substantially the wear-resistance without the sacrifice of the corrosion–resistance. It has been shown that the plasma ion implantation at elevated temperature is favorable for a thick modified layer for the realistic engineering applications and this plasma immersion ion bombardment is also used as an effective heating method[1]. More recently plasma process of the worpiece(s) has been developed to accomplish heating more quickly and efficiently than alternative approaches. The workpieces bias voltage biases the workpieces negatively as a cathode relative to the chamber wall, which acts as an anode. The bias potential serves to control the amount of the ion or electron bombardment of the workpiece surface and heating the components.

During the plasma immersion ion processing, such parameters as implantation voltage, plasma density, pulse duration, pulse frequency, etc. have a great influence on the implanted dose and resultant target temperature, which unequivocally determine the surface modification results. In this paper we present the ion–heating model and analyze the effect of the implantation parameters on the target temperature.

2. Model

When a sudden negative high voltage is applied to the target, then, initially, in the time scale of the inverse electron plasma frequency, electrons near the surface are driven away, leaving behind a uniform density ion "matrix" sheath. Subsequently, on the time scale of the inverse ion plasma frequency, ions within the sheath are accelerated into the target. This, in turn, drives the sheath–plasma edge further away, exposing new ions that are extracted[4].

During and after matrix sheath implantation, a quasistatic child–law sheath forms. The current demanded by this sheath is supplied by the uncovering of the ions at the moving sheath edge. The drift of ions tarward the target is ignored. This is feasible in the case of a fast sheath since the presheath does not have time to form before the sheath reaches a given point[5].

The child–langmiur relation for one–dimensional infinite plane is

$$j = \frac{4}{9}\varepsilon_0(\frac{2e}{M})^{0.5}\frac{V_0^{1.5}}{S^2} \tag{1}$$

where ε_0 is the free–space permittivity, e is the ion charge, M is the ion mass, S is the sheath thickness, V_0 is the applied voltage.

Owing to the assumption that the target ion current is provided only by the uncovering of the ions, so that

$$j = qn_i\frac{\mathrm{d}s}{\mathrm{d}t} \tag{2}$$

where n_i is the density.

Combining Eq. (1) and Eq. (2), the sheath expansion velocity for a planar geometry becomes

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{4}{9}\frac{\varepsilon_0}{n_i}(\frac{2}{qM})^{0.5}\frac{V_0^{1.5}}{S^2}. \tag{3}$$

This equation can be integrated analytically to yield

$$S_{(t)} = S_0(\frac{2}{3}W_{pi}t + 1)^{\frac{1}{3}} \tag{4}$$

where $W_{pi} = u_0/s_0$ is the ion plasma frequency, $S_0 = (2\varepsilon_0 V_0/qn_i)^{0.5}$ is the initial ion–matrix sheath thickness, and $u_0 = (2qV_0/M)^{0.5}$ is the characteristic ion velocity. Thus ion current

$$J = \frac{2}{9}\varepsilon_0(\frac{2e}{M})^{0.5}\frac{qn_i}{\varepsilon_0}\frac{V_0^{0.5}}{(\frac{2}{3}W_{pi}t + 1)^{\frac{2}{3}}} \tag{5}$$

Assuming that all the ions in the sheath are implanted into the surface with energy of eV_0, the ion heating power is

$$P = V_0 J \tag{6}$$

The energy deposited by the ions in a single pulse can be obtained through integration

$$W = \int_0^p p\mathrm{d}t. \tag{7}$$

It is obvious that W monotonously decreases with the time in a single pulse owing to the child relationship of the sheath. Meanwhile the PIII process features very large heating fluxes applied to the target in a short period of time and pulse working conditions. Therefore it is extremely difficult to calculate the target temperature pulse by pulse. Here the temperatures may be modeled by averaging the input power over the full cycle and it is reasonable in the regular PIII processes[6]. The average heating power is

$$P_{ave} = f \cdot W \tag{8}$$

where f is the pulsing frequency.

If we ignore the instantaneous dynamic ion heating process, in simplicity the deposited energy can be calculated by the sheath width at the end of the pulse, thus

$$P_{ave} = f n_i^{0.5} V_0^{1.5} (2e\varepsilon_0)^{0.5} (\frac{2}{3}(\frac{n e^2}{\varepsilon_0 M})^{0.5} t + 1)^{\frac{1}{3}}. \tag{9}$$

For the realistic implantation process, e.g. $n_i = 5.0\times10^{15}/\mathrm{m}^3$, N_2^+ plasma, t_p=20μs, $\frac{2}{3}(\frac{n e^2}{\varepsilon_0 M})^{0.5} t = 240 \gg 1$, thus Eq. (9) can be simplified as

$$P_{ave} = (\frac{2}{3})^{\frac{1}{3}} 2^{\frac{1}{2}} e^{\frac{5}{6}} \varepsilon_0^{\frac{1}{3}} t^{\frac{1}{3}} M^{\frac{1}{6}} f V_0^{1.5} n^{\frac{2}{3}}. \tag{10}$$

3. Results and Discussion

It is evident from Eq. (10) that the heating power is related to the implantation voltage, plasma density, ion mass, pulse duration and pulse frequency, etc. The voltage and plasma density have a greater influence on the ion deposition energy density. Fig.1 is the calculated results for a plasma density of $n_i = 5.0\times10^{15}/\mathrm{m}^3$ and a implantation voltage of V_0=50kV respectively. The curves demonstrate that the ion heating power exponentially increases when the voltage and plasma density increase, just as indicated by Eq.(10). It also infers that the ion heating power is more influenced by the plasma density in the low density case than in the high density case.

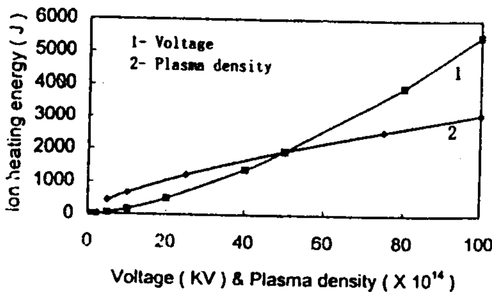

Fig.1 The influence of voltage and plasma density on ion heating power with a pulse duration of 20μs.

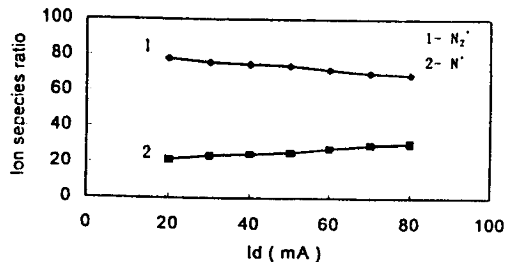

Fig.2 The ion species ratio at a N_2 pressure of P=2.0$\times10^{-4}$Torr.

In contrast when the higher voltage implantation is conducted, a little increase in voltage not only enlarges substantially the sheath thickness, but also increases the energy of each ion, therefore the target temperature will be more sensitive to the implantation voltage in the high voltage process than in the low voltage process. In realistic PIII process, plasma density is usually adjusted through the input power of RF plasma source or discharge current of hot filament glow discharge plasma source. In fact when the source power increases, the plasma density in the vacuum chamber increases, meanwhile the ion species ratio also changes. Fig.2 indicates the results measured in a nitrogen plasma as a function of discharge current in the hot filament glow discharge case. It is obvious that the N_2^+ percentage decreases and the N^+ percentage increases gradually with discharge current.

Based on the work of Qinshu et al[7], a dynamic sheath model of a multiple–species plasma has been developed, in which equ (4) is still effective, however

$$\sqrt{M} = K_1\sqrt{m_1} + K_2\sqrt{m_2} \tag{11}$$

where K_1 and K_2 are the fractions of the total ion density in the plasma bulk for species and species 2 respectively, and m_1, m_2 the ion mass for these two ions. In our case of I_d=80mA, the ratio of N^+ plasma density to N_2^+ plasma density is 30:70[8], thus M is calculated and equal to 23.3, which increases further ion heating power density according to Eq. (10). That is to say, when a plasma density increases, the ion heating power density increases owing to not only the plasma density variation but also the ion species ratio change. This demonstrates that a low voltage ion implantation[9] at elevated temperature, H_2 or He may be used as a diluent gas in N_2 atmosphere, helping to maintain a high temperature besides cleaning the surface oxides, which is just alike the conventional plasma nitriding. In fact during the semiconductor treatment using the PIII technique, hydrogen ion implantation produced an evidently higher temperature rise rate than oxygen ion implantation when we measured the target temperature in–situ using a thermocouple[10] which was shielded by stainless steel tube.

For two–dimensional target of a thin cylindrical copper platen with a diameter of 120mm and a thickness of 6 mm, we used fluid models to simulate the dynamic sheath and then calculated the target temperature. The governing equations[11,12] are

$$\frac{\partial n}{\partial \tau} + \frac{1}{R}\frac{\partial}{\partial R}(Rnu_R) + \frac{\partial}{\partial z}(nu_z) = 0 \tag{13}$$

$$\frac{\partial u_R}{\partial \tau} + u_R\frac{\partial u_R}{\partial R} + u_z\frac{\partial u_R}{\partial z} = \frac{1}{2}\frac{\partial \varphi}{\partial R} \tag{14a}$$

$$\frac{\partial u_z}{\partial \tau} + u_R\frac{\partial u_z}{\partial R} + u_z\frac{\partial u_z}{\partial z} = \frac{1}{2}\frac{\partial \varphi}{\partial z} \tag{14b}$$

$$\frac{\partial^2 \varphi}{\partial R^2} + \frac{1}{R}\frac{\partial \varphi}{\partial R} + u_z\frac{\partial^2 \varphi}{\partial z^2} = 2[n - \exp(\frac{e\phi_t}{KT_e}\varphi)] \tag{15}$$

$$k\Big(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r}) + \frac{\partial^2 T}{\partial z^2}\Big) + H = \rho c\frac{\partial T}{\partial t} \tag{16}$$

The dimentionless variables are $R = x/S_0$, $Z = z/S_0$, $\varphi = \phi/\phi_t$, $n = n_i/n_0$, $u_R = v_{iR}/u_0$, $u_Z = v_{iZ}/u_0$, $\tau = t/\omega_{pi}$, ρ is the density of the target materials, c is the heat capacity, and H is heating power.

The simulation results demonstrate that the space temperature difference of the whole target is small as shown in Fig.3, because the target used in the experiments and simulations is samall and the copper alloys posesses a higher thermal conductivity, giving rise to a higher thermal diffusion coefficient, therefore the heat is easily transferred to other religion with a little lower temperature, and cosequently the temperature dufference within the target is less than 2°C[13].

The Fig.4 shows the effect of the implantation parameters on the target temperature for 2kV/10kHz/16μs. It is evident that the plasma density and implantation voltage have a substantially different influence factor on the temeparure during the PIII processes. it also demonsdtrates that the voltage has a greater effect on the target temperature than the plasma density.

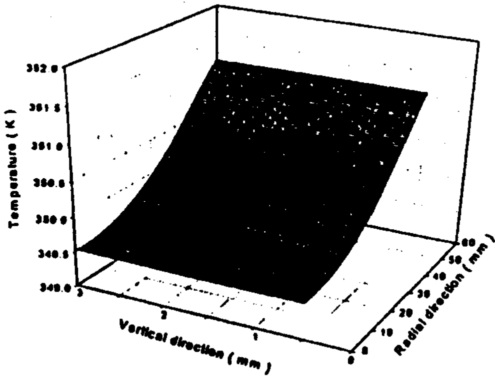

Fig.3 The temperature distribution in the copper target at t=300s (Only a quarter of the target is shown owing to the semmetry and treatment conditions: 2kV/10kHz/16μs with a plasma density of $5.0\times10^{15}/m^3$).

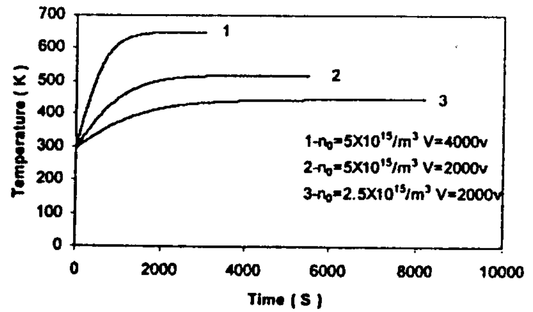

Fig.4 The effect of the implantation parameters on the target temperature rise.

4. Conclusion

It is critical to control treatment temperature in plasma ion processing. Such parameters as implantation voltage, plasma density, ion mass, pulse duration, pulse frequency and so on have a great influence on the sheath and resultant temperature of target or components. We have developed a one–dimensional theoretical model to calculate the ion heating flux and two–dimensional model to simulate the temeprtaure of the cylindrical target. The results indicate that the implantation parameters have an evidently different influence factor on the target temperature. It is more effective to control the target temperature by adjusting the imlantation voltage than by changing the plasma density. When the plasma density is increased in realistic applications, the temperature rise comes from not only the plasma density increase but also the ion equavalent mass change.

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