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Theoretical Analysis of Plasma Parameters on Film Deposition in planer and Cylindrical Magnetron Sputtering

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Thin film deposition using plasma sputter is done by experimental methods, though Numerical simulation and theory are capable of generating realistic and useful results. In present exploration a theoretical model for sputtering with consequence of different plasma parameters with the help of electromagnetic lenses for planar (T_p) and cylindrical (T_c) magnetron sputteringhas been conversed. The plasma of helium gas on nickel metal objectwhich contains the velocity shear instability is considered, and T_p,T_c, under the influence of shear scale length(A_i), homogeneous DC electric field(E_0), magnetic field (B_0), density gradient ($\varepsilon_n\rho_i$) have been evaluated. T_p, and $T_c$are found to be maximum in the range of 0.815–0.91, and 0.57–0.90, respectively. Also growth rate showed direct relation to E_0 and A_i but inversely varies with B_0 and $\varepsilon_n\rho_i$.

Keywords: Coating, Morphology, Plasma, Sputtering, Surface

1 Introduction

Sputtering is understood as a momentum transfer process and is one of the most important thin film fabrication technique, in which metal, alloy and compounds directly deposited on substrate at higher rate with least damage of surface[1,] imparting desired properties suitable for aerospace, automotive and in specific industrial applications[2–5]. Generally, sputtering is energetic ion bombardment in an enclosed chamber in the presence of nobel gas, by glow discharge. An electric potential produces plasma between two electrodes (cathode and anode known as target and substrate), once the ion with in plasma with energy above threshold energy incidences on target, the atoms of target get dislodged or sputters and get deposited on substrate material.

It is evident that sputter is possible at ion energy ranging from 30 eV to 700 eV[6]. This present opportunities to practically sputter surface at low energy range (1000 eV)[7,8]. It has been reported that it is possible to achieve target DC power densities to several tens of W cm^{-2} *i.e.* 900 Wcm^{-2}due to presence of magnetron plasma close to cathode target which could be very dense (10^{12}–10^{13} cm^{-3})[9]. Majority of ions extracted near the negatively biased substrate, are of working gas and plasma densities are lower in the range of 10^9 to 10^{10} cm^{-3} in such specimens. Reactive magnetron sputtering is a popular technique presenting a primary advantage of ion assisted growth with high deposition rate. On surface of growing film during such conditions ion-to-metal flux ratio are relatively small *i.e.* in the order of 0.1-1[10].

Two most common magnetron sputtering designs are planar and cylindrical magnetron sputtering. Both techniques has an array of magnets behind the targets arranged in such a fashion that E x B (electric and magnetic field) forms a closed loop, cathodes operating at 300–700 V and giving current density ranging from 04-60 mAcm^{-2}.

Control of plasma and coating parameters is upmost requirement to obtain good crater free film as high power beam may change surface morphology hence affecting product performance[2,11]. For predicting ion interaction to target surface various statistical models are implemented by researchers for stablishing experimental investigations. The numerical simulation presents a great scope towards predicting or archiving results compared to physical setup[12,13]. These simulations are capable of providing fast computational systems at reduced cost. With these improvements in models and mathematical algorithms systems are able to work properly with more realistic problems.

The aspire of this work is to compute relative thickness of the film for planar and cylindrical magnetron sputtering using mathematical models, considering the parameters of helium plasma and their effect on relative thickness deposited on Nickel surface.

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2 Methodology

In this study plasma is generated by using Helium gas using the D.C. electric field. In plasma wave, particle interactions are broadly categorized as electrostatic instabilities, and electromagnetic stabilities[14]. Any perturbation to the equilibrium state of plasma, displaces the charged particles, those in turn set up electric and magnetic field acting as restoring fields[15,16]. These instabilities are responsible for diffuse aurora, electron-ion cyclotron, plasma frequency turbulence *etc.* collectively known as spontaneous emissions that controls plasma dynamics.

In this study the assessment of electric, magnetic field and other plasma factors are selected as reported by Merlino *et al.* [9],to breed Helium plasma. The parameters temperature anisotropy (A_T = 0 to 1.5) $A_T = \frac{T_{\perp i}}{T_{\|i}} - 1$ with s hear scale length = 0.50, 0.55, and 0.60, temperature ratio ($\frac{T_e}{T_i}$ = 2), magnetic field (0.16 T to 0.24 T), electric field (0 to 16 Vm^{-1}), density gradient ($\varepsilon_n\rho_i$ = 0 to 0.9) and in homogeneity in DC electric field (0 to 0.6) were used.

In this study, thermal energy of electron ($K_B\ T_{\|e}$) has taken higher as compared to that of ions ($K_B\ T_{\|i}$), resulted the ratio of T_e / T_i is greater than 1 and therefore investigation has be made for ion waves. Other parameters which are entail for calculating the value of thin film thickness for planar and cylindrical magnetron sputtering have been taken as reported by Grais *et al.*[8] and Meng *et al.* [17]. The parameters for He^+/Ni are k = 0.1, β = 7.218 × 10^{-3}, Ω = 0.571, and h= 0.4R to 2R.

Helium gas is influenced by magnetic and electric field where the diameter of plasma column is 4 cm and spot size of plasma ions is 2-6 mm, depending upon the degree of focusing of electromagnetic lenses[18,19].

The velocity of ions (v_i) is computed with the help of real frequency of the waves [20] using Eq. 1.

Since,

$$\text{Real frequency of waves} = \frac{b_1}{2a_1}$$

$$v_i = \text{Group Velocity of ions/waves } = \frac{b_1}{2a_1} \times \frac{\Omega_i}{K_{\|}} \qquad \dots (1)$$

where constants a_1 and b_1 are calculated as:

$$a_1 = a_2\left(\frac{\Omega_i}{K_{||}\alpha_{||}}\right)^2 \text{, and}$$

$$b_1 = \frac{\Omega_i}{K_{||}\alpha_{||}} b_2 - \frac{2\mathrm{K}_{\perp}\Delta'}{K_{||}^2\alpha_{||i}^2} a_2\Omega_i$$

$K_{\|}$ is wave number in direction of magnetic field, Ω_i is Gyro frequency,

Gyro frequency (Ω_i) and wave number in direction of magnetic field ($K_{/\!/}$) are obtained by linearizing Vlasov-Maxwell equation for homogenous plasma and doing small perturbation in electric and magnetic fields in order to obtain dispersion relation.

The values of constant a_2 and b_2 can be calculated as:

$$a_2 = \frac{\eta_e}{\eta_i}\frac{T_{\perp i}}{T_{||i}} + \frac{T_{\perp i}}{T_{||i}} - \Gamma_n(\mu_i)\frac{T_{\perp i}}{T_{||i}}$$

$$b_2 = \frac{\Gamma_n(\mu_i)k_{\perp}}{2k_{||}}\varepsilon_n\rho_i\frac{\alpha_{\perp i}}{\alpha_{||i}} - \frac{\Gamma_n(\mu_i)k_{\perp}}{2k_{||}} - \frac{\Gamma_n(\mu_i)k_{\perp}n\Omega_i}{2k_{||}^2\alpha_{||i}}$$

Here Γn is the modified Bessel function of order n, p, temperature of ions in the direction of electric field and in the direction of magnetic field are represented as $T_{\perp i}$ and $T_{||i}$respectively, log mean plasma density gradient is ε_n, gyro radius of ions is ρ_i, wave number in the direction of electric field and in the direction of magnetic field are represented by $k_{\perp}$ and $K_{\|}$ respectively, $\alpha_{||i}$being thermal velocity in magnetic field, α is thermal velocitv of ions,

$$\eta_i = 1 - \frac{\overline{E_i}'(x)}{4\Omega_i^2}, \eta_e = 1 - \frac{\overline{E'_e}(x)}{4\Omega_e^2}, \overline{\omega}' = \overline{\omega} - n\Omega_i$$

value of E' (x) is the derivative of $E(x) = E_0\left(1 - \frac{x^2}{a^2}\right)$ and$\overline{E}(x) = \frac{e_sE(x)}{m_s}$,

whereas E_0 is magnitude of homogenous direct current electric field at origin and E(x) is magnitude of homogeneous Direct current electric field with respect to distance x from origin.

$$\Omega_s = \frac{e_sB_0}{m_s}, \alpha_{\perp s} = \left(\frac{2K_BT_{\perp s}}{m_s}\right)^{1/2}, \alpha_{||s} = \left(\frac{2K_BT_{||s}}{m_s}\right)^{1/2}$$

e_s is charge of species and B_0 magnitude of magnetic field (T), k_B Boltzmann constant

The unperturbed bi-Maxwellian distribution function can be written as:

$$f_{so} = f_{smo} + \upsilon_{oy}\,\xi$$

$$\xi = \frac{\overline{\omega} - (n+p)\Omega_s - K_{\perp}\Delta'}{K_{||}\alpha_{||s}},$$

$$\varDelta' = \frac{\partial \varDelta}{\partial t},$$

$$\varDelta = \frac{\overline{E}(x)t}{\varOmega_s}\left[1 + \frac{E''(x)}{E(x)}.\frac{1}{4}\left(\frac{v_\perp}{\varOmega_s}\right)^2\right]$$

Where $\varDelta' = \frac{\partial \varDelta}{\partial t}$ represents the drift velocity

$$\varGamma_n(\mu_s) = exp(-\mu_s)\, I_n(\mu_s),\ \mu_s = \frac{k_\perp^2 \rho_i^2}{2},$$

$I_N(\mu_s)$ being a modified Bessel function

$$\left(\frac{E_{th}}{E_i}\right)^{\frac{1}{\Omega}} = \frac{2}{3}\left(\frac{1.2^2 - (0.8\beta)^2 E_i^{1.3}}{0.8 - (0.75\beta^2)E_i^{0.8} - \left(\frac{1}{\Omega}\right)\left(1.2 + (0.8\beta)E_i^{0.67}\right)}\right) \quad \ldots (2)$$

E_{th} target materials threshold energy usually sublimation energy, β is width of loss cone distribution function

$$E_i = \frac{m_i v_i^2}{2} = eV \quad \ldots (3)$$

Than relative thickness of the film for planar magnetron/ cylindrical magnetron sputtering is premeditated by using Eq. (1) – (3).

The relative thickness of the film for planar magnetron sputtering is calculated using Eq. 4.

$$T_p = h^2(T_{p1} - \alpha h^2 T_{p2}) \quad \ldots (4)$$

Here substrate to target height is h with ϕ as azimuthal angle

$$T_{p1} = 2\int_{R_1}^{R_2} RdR \int_0^{\pi} \frac{d\phi}{L_0^5 (1 - K\cos\phi)^{5/2}}$$

$$T_{p2} = 2\int_{R_1}^{R_2} RdR \int_0^{\pi} \frac{d\phi}{L_0^7 (1 - K\cos\phi)^{7/2}}$$

$$\alpha = \frac{5}{3}\left(\frac{E_{th}}{E_i}\right)^{1/2} / \left[1 - \left(\frac{E_{th}}{E_i}\right)^{1/2}\right]$$

$$K = \frac{2Rr}{L_0^2}$$

$$L_0^2 = R^2 + r^2 + h^2$$

The relative thickness of the film for cylindrical magnetron sputtering is calculated by Eq. 5[17] R, and r, are the radius of plasma column, and radius of plasma nozzle, respectively.

$$T_c = T_{c1} - \alpha T_{c2} \quad \ldots (5)$$

Where $T_{c1} = \int_h^{h+1} hdh \int_0^{2\pi} R_2 d\phi \frac{(R_2 - r\cos\phi)}{L_0^5 (1 - K\cos\phi)^{5/2}}$

$$T_{c2} = \int_h^{h+1} hdh \int_0^{2\pi} R_2 d\phi \frac{(R_2 - r\cos\phi)^3}{L_0^7 (1 - K\cos\phi)^{7/2}}$$

3 Results and Discussion

Statistical exploration with the help of computer technique and mathematical model on relative thin film thickness for planar and cylindrical magnetron sputtering is systemically investigated, using principle of velocity shear instability by means of permutation of plasma parameters.

Figure 1 (a-b) show the variation of thickness of film deposited by planar magnetron sputtering (T_P) and cylindrical magnetron sputtering (T_C) vs h/R_2 for

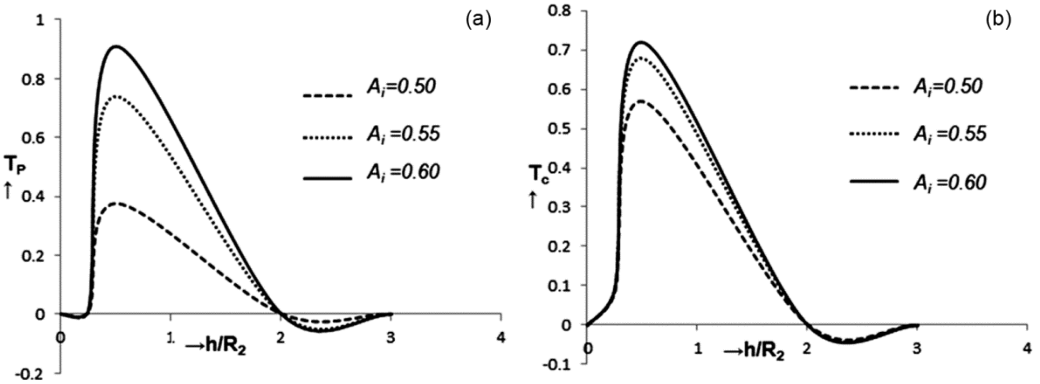

Fig. 1 — Variation of film thickness (a) T_P vs h/R_2, (b) T_c vs $h/R_2$for different values of A_i at parameters T_e/T_i = 2, E_0=0 Vm^{-1}, θ = 88.50, A_T=1.5, $\varepsilon_n \rho_i$ = 0.2, B_0=0.24 T.

different values of shear scale length (A_i) and other fixed parameters. The thickness increased with increasing the values of shear scale length. The maximum thickness T_P, T_C, are 0.91, and 0.72, respectively at value of shear scale length 0.60; and minimum values are 0.375, and 0.57, respectively, at value of shear scale length 0.50.As there is increase in value of shear scale length (A_i) an increase in growth rate is observed along with slight increase in band width with A_i, but the maxima of band does not shift. The peak value of T_c is maximum at 0.68, whereas that of T_p is 0.74. Velocity shear is considered the source of instability, as non-uniform velocity shear is reason behind coupling. And coupling of regions of negative and positive wave energy presents mechanism for instability of this node.

Figure 2(a-b) show the variation of thickness of film deposited by cylindrical magnetron sputtering (T_C) and planar magnetron sputtering (T_P) vs h/R_2 for different values of homogeneous DC electric field (E_0) and other fixed parameters. The thickness increased with increasing homogeneous DC electric field. The maximum thickness T_P, T_C, are 0.86, and 0.90, respectively, at value of homogeneous DC electric field 16 Vm^{-1}; and minimum values are 0.375, and 0.57, respectively, at value of homogenous DC electric field of 0 Vm^{-1}.With increasing value of electric field the real frequency increases. With increase in the value of homogeneous DC electric field from 0 to 16 Vm^{-1} increase in growth rate is observed. The resonant and non-resonant interactions affect real frequency and the growth rate. These result will assist in designing the machine such as metal cutting and cold spray capable of controlling frequency and velocity of the wave.

Figure 3(a-b) show the variation of thickness of film deposited by planar magnetron sputtering (T_P) and cylindrical magnetron sputtering (T_C) vsh/R_2 for different values of magnetic field (B_0)and other fixed parameters. The thickness decreased with increasing magnetic field (B_0). The maximum thickness T_P, T_C, are 0.815, and 0.57, respectively, at value of magnetic field (B_0) of0.16 T; and minimum values are 0.375, and 0.37, respectively, at value of magnetic field

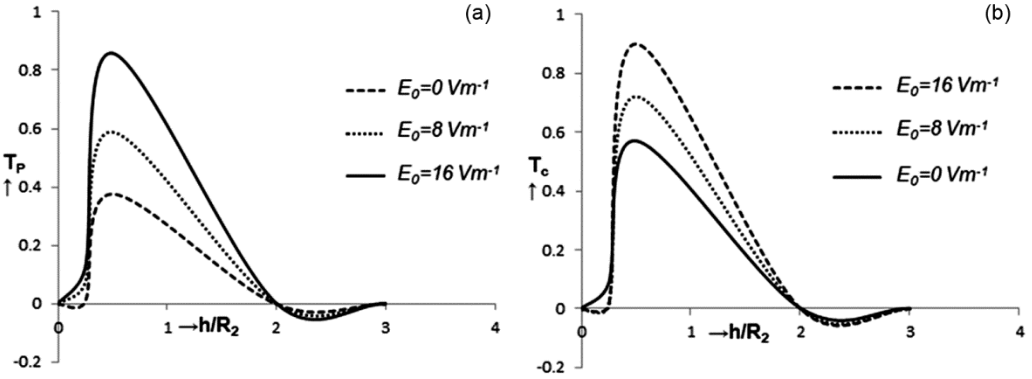

Fig. 2 — Variation of film thickness (a) T_P vs h/R_2, (b) T_c vs $h/R_2$for different values of E_0at parameters $T_e/T_i = 2$, A_i=0.5, θ = 88.50, A_T =1.5, $\varepsilon_n\rho_i$ = 0.2, B_0=0.24 T.

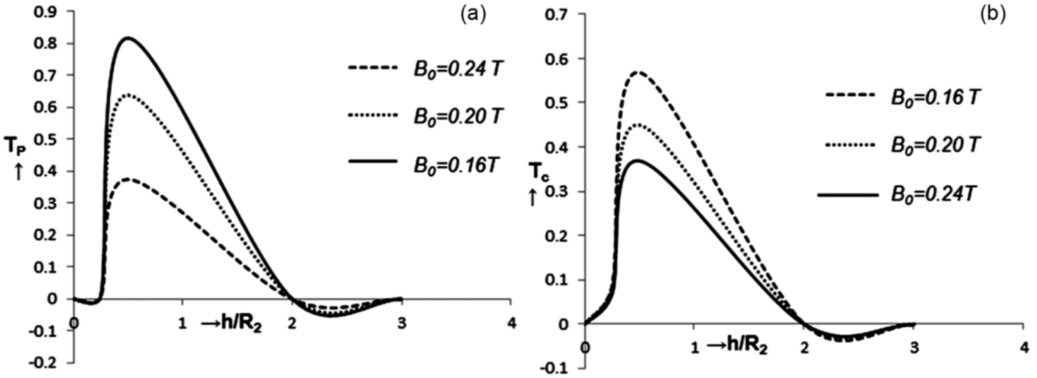

Fig. 3 — Variation of film thickness (a) T_p vs h/R_2, (b) T_c vs $h/R_2$for different values of B_0at parameters T_e/T_i = 2, A_i=0.5, θ = 88.50, A_T =1.5, $\varepsilon_n\rho_i$ = 0.2, E_0=0.

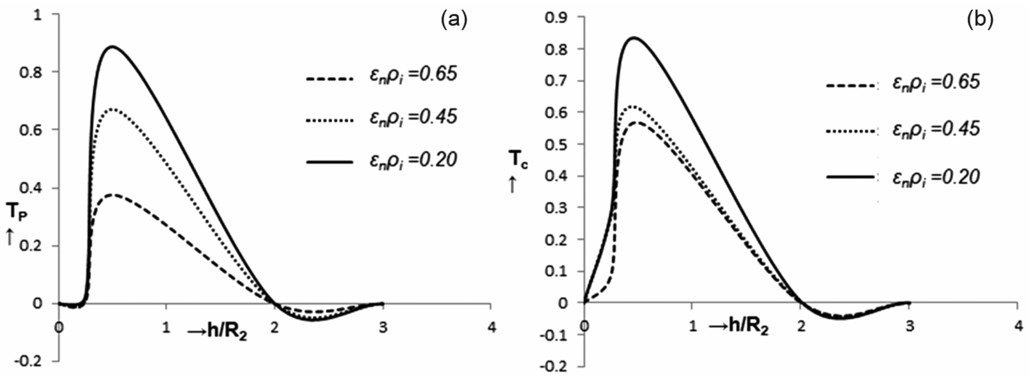

Fig. 4 — Variation of film thickness (a) T_p vs h/R_2, (b) T_c vs $h/R_2$for different values of $\varepsilon_n\rho_i$at parameters E_0=0, T_e/T_i = 2, A_i=0.5, θ = 88.50, A_T =1.5, B_0 = 0.2.

(B_0) is 0.24 T. This happens due to change in magnetic field gyro frequency. Thus magnetic field strength becomes a useful parameter for machining processes. The positive and negative energy waves coupled in a homogenous magnetic field influences the growth rate. The real frequency and growth rate decreased with increasing the magnetic field strength also as it has been observed that higher magnetic field discharge current saturates thus influencing growth rate [21]. Due to change in magnetic field the gyro-frequency has been changed. A useful parameter for required velocity of electrostatic ion cyclotron wave emerges as magnetic field strength. Hence, this is useful result for designing a machine for metal cutting machines and cold spray machines.

Figure 4 (a-b) show the variation of thickness of film deposited by planar magnetron sputtering (T_P) and cylindrical magnetron sputtering (T_C) vsh/R_2 for different values of density gradient ($\varepsilon_n\rho_i$) and other fixed parameters. The thickness increased with decreasing the value of density gradient. The maximum thickness T_P, T_C, are 0.889, and 0.832, respectively, at value of density gradient of 0.20; and minimum values are 0.375, and 0.57, respectively, at value of density gradient of 0.65.Usually, after increasing a certain value (0.5) of h/R_2, growth rate is drastically reduced.

The value of thickness (T_p, T_c) of film deposited by planer and cylindrical magnetron sputtering varies from 0 to 0.87 as reported by Meng *et al.* and Pushkarev *et al.*[11,17]. The theoretical results obtained from the given mathematical model and computer technique are found out within this range.

It has been found that the effect of in homogeneity in DC electric field , magnetic field, electric field, shear scale length, density gradient affects significantly thin film thickness for planar and cylindrical magnetron sputtering. Planer magnetron has always shown better growth comparative to cylindrical magnetron. For increasing value of DC electric field (E_0) and shear scale length (A_i) growth rate increased, where as with decreasing the value of magnetic field (B_0), and density gradient ($\varepsilon_n\rho_i$), growth rate increased.

4 Conclusions

In this paper, model of sputtering machine for thin film thickness for planar and cylindrical magnetron sputtering based on the principle of velocity shear instability are elaborated. The relative thin film thickness is able to proscribe by anecdotal different parameters for instance electric field, shear scale length, magnetic field. Based on these the following conclusions are drawn.

1. The maximum thickness T_P, T_C, are 0.91, and 0.72, respectively at value of shear scale length 0.60; and minimum values are 0.375, and 0.57, respectively, at value of shear scale length 0.50, respectively keepingother parameters fixed.
2. The maximum thickness T_P, T_C, are 0.86, and 0.90, respectively, at value of homogeneous DC electric field 16 Vm^{-1}; and minimum values are 0.375, and 0.57, respectively, at value of homogenous DC electric field of 0 Vm^{-1} keeping other parameters fixed.
3. The maximum thickness T_P, T_C, are 0.815, and 0.57, respectively, at value of magnetic field (B_0) of 0.16 T; and minimum values are 0.375, and 0.37, respectively, at value of magnetic field (B_0) is 0.24 T keeping other parameters fixed.
4. The maximum thickness T_P, T_C, are 0.889, and 0.832, respectively, at value of density gradient of 0.20; and minimum values are 0.375, and 0.57, respectively,

at value of density gradient of 0.65 keeping other parameters fixed.

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