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The effects of plasma characteristics on the melting time at the front surface of a film on a substrate: An exact solution

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Abstract

Plasma heating of a film on a substrate is solved by using the Laplace transform method. The plasma is composed of a collisionless presheath and sheath on an electrically negative bias film partially reflecting and secondly emitting ions and electrons. The heating of the film from the plasma accounting for the presheath and sheath is determined from the kinetic analysis. This work proposes an analytical model to calculate the melting time and heating rate of the front surface of a film on the substrate, and provides quantitative results applicable to control the temperature evolution and the melting time in the film. The predicted surface temperature of the film on the substrate as a function of time is found to agree well with experimental data. The effects of dimensionless bias voltage, reflectivities of the ions and electrons on the wall, electron-to-ion source temperature ratio at the presheath edge, ion-to-electron mass ratio, charge number, plasma flow work-to-heat conduction ratios, substrate-to-film solid thermal conductivity ratios, and film-to-substrate solid specific heat ratios on the melting time and heating rate of the front surface are obtained. The contact Biot number between the film and substrate to simulate the heat conduction into substrate is also discussed. The results show that the melting time is strongly dependent on the plasma parameters and thermal properties of the material.

Keywords: Plasma energy flux; Sheath; Presheath; Negative bias voltage; Melting time; Heating rate

1. Introduction

Plasma etching, spray deposition, sputtering, cutting, surface treatment, and nuclear fusion devices, etc. are controlled by energy transfer from the plasma to surfaces. When a plasma is in contact with a workpiece surface, a thin layer called the sheath or space-charge region exists on the wall [1]. The presheath ($\sim 10^{-4}$ m), which lies between the bulk plasma and sheath, is an ionization region to supply the ions lost to the wall and accelerates the ions up to and beyond sonic speed before entering the sheath, as first explicitly pointed out by Bohm [2]. Heat transport in the workpiece is determined by the plasma energy transfer, which is controlled by the parameters such as the charge number, mass and temperature ratios of the ions and electrons generated in the presheath, and properties of the wall, etc. Several plasma-based techniques may be employed

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Nomenclature

B	defined in Eq. (18)
Bi	Biot number, $Bi = h_\infty s/k_f$, $Bi_a = h_a s/k_f$, $Bi_c = h_c s/k_f$
C_p	specific heat
C_{pfs}	the ratio of specific heat, $C_{pfs} = c_{pf}/c_{ps}$
D	Dawson function
e	electron charge
E_i	dimension and dimensionless ionization energy, $E_i = E_i/k_B T_{e0}$
h	heat transfer coefficient
j	dimension and dimensionless current density, $j = j/en_{e0}(K_B T_{e0}/m_i)^{1/2}$
k	solid thermal conductivity
k_B	Boltzmann constant
K_{sf}	substrate-to-film solid thermal conductivity ratio, $K_{sf} = k_s/k_f$
m	particle mass
M	ion-to-electron mass ratio, $M = m_i/m_e$
n	particle density
Q	dimension and dimensionless total energy flux $Q = Q/[n_{e0}k_B T_{e0}(k_B T_{e0}/m_i)^{1/2}]$
s	the thickness of thin film
t	time
T	temperature
x	Cartesian coordinate
Z_i	charge number

Greek symbols

Θ	plasma flow work-to-thermal conduction ratio, $\Theta = n_{e0}k_B T_{e0}(k_B T_{e0}/m_i)^{1/2}/(k_f T_\infty/s)$
ε	defined in Eq. (18)
λ	dimensionless temperature, $\lambda = (T - T_\infty)/T_\infty$
α	dimensionless thermal diffusivity
ξ	dimensionless coordinate, $\xi = x/s$
φ	dimension and dimensionless work function, $\varphi = \varphi/k_B T_{e0}$
κ	electron-to-ion source temperature ratio at presheath edge, $\kappa = T_{e0}/T_{i0}$
γ	reflectivity
ρ	density
ρ_{fs}	the ratio of density, $\rho_{fs} = \rho_f/\rho_s$
τ	dimensionless time, $\tau = k_f t/\rho_f c_{pf} s^2$
ϕ, χ	dimensional and dimensionless potential, $\chi = -e\phi/k_B T_{e0}$
Ω, Ω_{1b}	functions, defined in Eqs. (2) and (4), respectively

Subscripts

b	boundary between sheath and presheath
bias	negative bias voltage
e, i	electron and ion
f	floating condition or a film
ff	finite film
m	melting
s	substrate
tot	total
w	wall
0, 0′	coordinate origin at $\phi = 0$ and $\xi = 0$, respectively, as shown in Fig. 1

to control energy and mass fluxes of the ions and electrons. For example, the application of a direct current (DC) bias or radio frequency (RF) bias can be used to accelerate the ions and retard the electrons from the plasma to the surface.

Thermal conditions at the workpiece surface play an important role in plasma–wall interactions. They strongly affect elementary processes, such as adsorption, desorption, diffusion, and chemical processes in semiconductor manufacturing and the lifetime of plasma facing materials in fusion devices. Especially in the case of thin film deposition, the structure and morphology of the layers depend sensitively on the thermal conditions at the surface. The surface temperature is strongly influenced by the plasma energy, due to energetic particle bombardment. Over the past decades there has been intensive research to study energy transport encountered in the cathode or near wall region of electric arc discharges, lamps, fusion devices, edge plasmas, ion implantation, deposition, etching, etc. [3–11]. Predictions of melting time, heating rate at the front surface and temperature distributions in a workpiece in contact with the plasma as functions of plasma characteristics and thermal properties of workpieces are still incomplete [12–16].

The aim of the present work is to solve the plasma heating of a film on a substrate by using the Laplace integral transform method. The film experiences heating induced by energy flux coming from the bulk plasma through the presheath and sheath to the surface, based on the analysis from a previous work [4]. In this study, a one-dimensional unsteady heat conduction model is developed to systematically predict unsteady temperature distributions in the film and substrate, and calculate the melting time and heating rate of the front surface of the film on the substrate subject to a negative bias voltage. The effects of the plasma characteristics and properties of the film and substrate on heating process of the film are quantitatively and rigorously provided.