Space periodic thermionic emission and ablation of metallic targets by crossed surface plasma waves

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Two surface plasma waves (SPWs) propagating at an angle to each other over a metal–free space interface, cause space periodic heating of electrons. As the electron temperature T_e rises, thermal conduction transverse to the interface and collisional heat transfer to the lattice become dominant heat-loss mechanisms. On the timescale of a few collision time, the lattice gets heated, giving rise to space periodic ablation that leads to the formation of grating structures. In case the SPW power is below the threshold for ablation, space periodic electron temperature results in space periodic thermionic emission.

LASER ablation of metallic targets and laser processing of thin metallic films is an area of great current interest for its applications in microelectronics[1–5]. The rate of ablation is seen to be enhanced dramatically when the laser couples to the surface plasma wave (SPW)[6,7]. The surface wave is an electromagnetic mode of wave propagation along the surface whose amplitude falls-off away from the interface in free space as well as inside the metal[8,9]. Its extent inside the metal is shorter than skin depth, while its spatial attenuation rate along the surface is weak. Hence SPW is more effective in heating and ablation of the surface. Ursu *et al.*[10] have given an excellent formalism of the energy coupling and transfer from laser radiation to metallic surfaces and SPW. Zherikhin *et al.*[11] have studied laser-induced decomposition, evaporation and ablation processes in 1-2-3 superconductors. Akhmanov *et al.*[12] have given an elegant review of physical effects taking place at the surfaces of the metals, semiconductors and dielectrics by the high-power radiation. Liu and Tripathi[13] have studied coupling between laser and SPW in the presence of a surface ripple. These studies employ a single SPW whose amplitude falls gently in the direction of propagation.

Currently, there is much interest in producing dot and grating structures. Ezaki *et al.*[14] have observed periodic, sub-micron size dot structures, where SPW plays an important role. In this communication we present a theoretical study of periodic surface heating and material ablation by two SPWs propagating at an angle with respect to each other. The superposition of SPWs causes heat transport along the surface. However, heat transport perpendicular to the surface is stronger as the SPW field decays rapidly in that direction. Electron–phonon collision causes space periodic heating of the lattice on pico-second time-scale, leading to periodic ablation of the material and creation of grating structures.

Consider a metal–free space interface, $x = 0$, with free space as region I ($x > 0$) and metal of effective permittivity ε as region II ($x < 0$). Two SPWs of equal frequencies propagate along the surface at angles θ and $-\theta$ to z-axis (Figure 1).

The fields of the two SPWs are,

$$\vec{E}_1 = \vec{F}_1(x)\exp[-i(\omega t - k\sin\theta\, y - k\cos\theta\, z)],$$

$$\vec{E}_2 = \vec{F}_2(x)\exp[-i(\omega t + k\sin\theta\, y - k\cos\theta\, z)], \tag{1}$$

where

$$\vec{F}_{1,2}(x) = A\left(-\frac{k}{i\alpha_1}\hat{x} \pm \sin\theta\hat{y} + \cos\theta\hat{z}\right)e^{-\alpha_1 x} \qquad \text{for } x > 0,$$

$$= A\left(\frac{k}{i\alpha_2}\hat{x} \pm \sin\theta\,\hat{y} + \cos\theta\,\hat{z}\right)e^{\alpha_2 x} \qquad \text{for } x < 0, \tag{2}$$

$\alpha_1^2 = k^2 - \omega^2/c^2$, $\alpha_2^2 = k^2 - \omega^2\varepsilon/c^2$, $k^2 = (\omega^2/c^2)[\varepsilon/(1+\varepsilon)]$, $\varepsilon \cong \varepsilon_L - \omega_p^2/\omega^2$, ε_L is the lattice permittivity and ω_p is the plasma frequency. The total field inside the metal is

$$\vec{E} = \vec{E}_1 + \vec{E}_2 = Ae^{\alpha_2 x}e^{-i(\omega t - k\cos\theta z)}\left[\hat{x}\frac{2k}{i\alpha_2}\cos(k\sin\theta\, y) + \hat{y}2i\sin\theta\,\sin(k\sin\theta\, y) - \hat{z}2\cos\theta\,\cos(k\sin\theta y)\right]. \tag{3}$$

This field imparts an oscillatory velocity $\vec{v}$ to free electrons. Solving the equation of motion $m(\mathrm{d}\vec{v}/\mathrm{d}t) = -e\vec{E} - m\nu\vec{v}$ we obtain,

$$\vec{v} = \frac{e\vec{E}}{mi(\omega + i\nu)}, \tag{4}$$

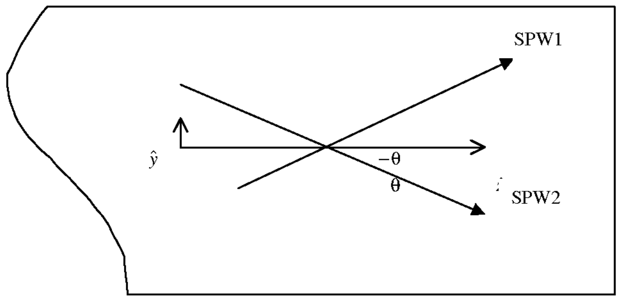

Figure 1. Schematic for propagation of two crossed SPWs at the metal–free space interface $x = 0$. The SPWs propagate at angles θ and $-\theta$ with respect to z, whereas their amplitudes fall-off exponentially in x.

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where $-e$, m and ν are electronic charge, mass and momentum transfer collision frequency. The SPWs heat the electrons at a time average rate $R = -e\vec{E}^{*}.\vec{v}/2$ where $*$ denotes the complex conjugate and real part of R is implied. Using eqs (3) and (4), one may write R as

$$R = \frac{\nu e^2 A^2}{m\omega^2 \varepsilon} e^{2\alpha_2 x}[\varepsilon - 1 - \cos(2k\sin\theta y)(1 - \varepsilon\cos 2\theta)], \quad (5)$$

where we have assumed $\nu^2 \ll \omega^2$. A steady state is reached when heating rate is balanced by the energy loss rate through electron–phonon collisions and thermal conduction,

$$R = -\nabla.(\chi_e \nabla T_e) + \frac{3}{2\tau_\varepsilon}(T_e - T_0), \quad (6)$$

where χ_e is the electron thermal conductivity, T_0 is the lattice temperature and τ_ε is the energy relaxation time. Assuming $\chi_e\tau_\varepsilon \gg \alpha_2^{-2}$, k^{-2}, and χ_e to be constant, the solution to eq. (6) can be written as

$$T_e = T_0 + T_1 e^{\alpha_0 x} + T_1' e^{2\alpha_2 x} + T_2 e^{2\alpha_2 x}\cos(2k\sin\theta y), \quad (7)$$

where

$T_1 = T_{e0} - T_0 - T_1'$, $T_1' = [\nu e^2 A^2(1-\varepsilon)]/[4m\omega^2\alpha_2^2\chi_e\varepsilon]$, $\alpha_0 = (2/3\tau_\varepsilon\chi_e)^{1/2}$, $T_2 = [\nu e^2 A^2(1 - \varepsilon\cos 2\theta)]/[4m\omega^2(\alpha_2^2 - k^2\sin^2\theta)\chi_e\varepsilon]$, and T_{e0} is the y-averaged surface temperature of electrons. At $x = 0$, T_e may be written as

$$T_e = T_{e0} + T_2\cos(2k\sin\theta\, y). \quad (8)$$

The rate of thermionic emission of electrons per unit area per second is given by Richardson formula[15],

$$I = C_1 T_e^2 e^{-e\phi/T_e}, \quad (9)$$

where ϕ is the work function of the metal and T_e is given by eq. (8). The periodicity of T_e in y results in y-periodic thermionic current. In Figure 2 *a* we have plotted normalized thermionic current, $I/C_1T_{e0}^2$ as a function of y and θ for $e\phi/T_0 = 30$, $\nu e^2A^2/(4m\omega^2\alpha_2^2\chi_e T_0) = 1$, $2\pi c/\omega = 1$ μm, $\omega_p/\omega = 3$, $\varepsilon_L = 2$, $\varepsilon = -7$.

The heated electrons impart energy to the lattice at the rate $\hbar\omega_{op}\nu' n_e$ per unit volume, where $\hbar\omega_{op}$ is the energy of an optical phonon, ν' is the electron–optical phonon collision frequency and n_e is electron density. The lattice temperature rises at the rate

$$\rho_L S\dot{T}_L = \hbar\omega_{op}\nu' n_e - \rho_L\bar{c}^2\nu'/4, \quad (10)$$

where ρ_L is the lattice density, S is the specific heat of the lattice and $\bar{c}$ is the average thermal speed of atoms. ν' is a strong function of electron temperature. As T_L reaches the melting point, the high temperature portion of the material melts and evaporates at the rate, $R_A = n_\ell\bar{c}/4$, where n_ℓ is the number of atoms per unit volume. We have solved eq. (10) numerically and shown the variation of time to attain the melting point for aluminum (933 K) with θ and y dimensions in Figure 2 *b*. The typical laser parameters for Al turn out to be $\lambda \sim 1.06$ μm, 10^{10} W/cm^2 (Nd : YAG laser). The plot shows a periodic behaviour, thereby indicating the formation of a periodic structure. The achievable periodicities are 600, 700 and 100 nm for $\theta = 30$, 45 and 60° respectively. On employing a single SPW, the θ and y variations of temperature are lost. However, the time required by a single SPW to reach the melting point is of the same order as that of the proposed scheme. Thus the process could be employed to create periodic dot and grating structures, as it has been found that mode-converted SPW is more effective in causing heating and emission of electrons when the laser spot size is larger by an order of magnitude or more than the laser wavelength[15]. The periodic density thus created may also lead to diffraction and parametric excitation of side band

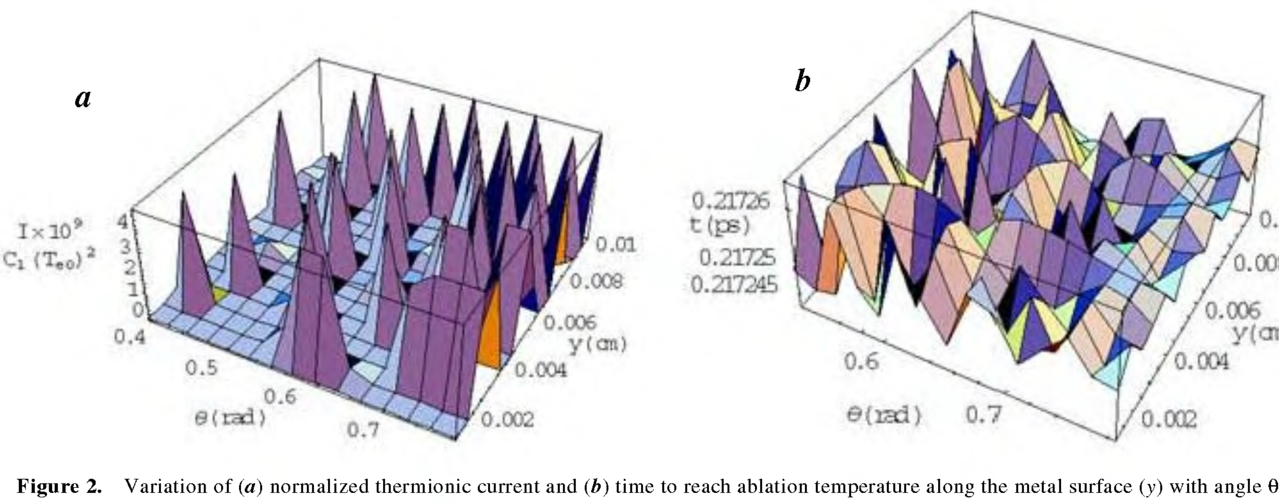

Figure 2. Variation of (*a*) normalized thermionic current and (*b*) time to reach ablation temperature along the metal surface (y) with angle θ.

SPW, thereby weakening laser–SPW coupling[13]. The two surface waves can be launched by employing the attenuated total reflection configuration[16], in which the electromagnetic wave is launched onto the prism–metal interface at an angle such that the component of propagation constant of the electromagnetic wave in the glass along the interface equals the propagation constant of the metal.

The process could go over to a parametric one[13], where initially a weak SPW is excited by surface roughness induced scattering from the incident field; the spatial modulation of the optical intensity resulting from the interference between the incident wave and the SPW can provide the growth of a periodic structure which increases the scattering into the SPW. Coupling to SPWs has shown to result in substantial field enhancement in the vicinity of a metal/dielectric interface. This could also serve as a diagnostic tool for various linear and nonlinear optical spectroscopic studies of the interface[12,17].

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Field measurements of sub-micron aerosol concentration during cold season in India

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Sub-micron particle size distribution and temperature were measured at six levels immediately above the ground surface during 8–16 December 1997 and 24–28 December 1998. Diurnal observations were made at every three-hour interval at all the levels. Continuous measurements of aerosol concentration were made from 0300 to 1000 h at 1 m level. During this period, particle concentration decreases from 0300 h, attains a minimum value between 0600 and 0700 h, and then maximum at 0900 h. Particles ≥ 0.075 µm show systematic variation in concentration, whereas particles < 0.075 µm show large fluctuations with time during 0300 to 1000 h. Concentration of particles of sizes 0.075–0.75 µm shows a minimum at 15-cm level where the temperature is maximum. However, particles of size 0.013 µm undergo Brownian diffusion and thus do not show any trend with temperature. The phenomena of thermophoresis and fog scavenging are discussed in terms of these results.

THERMOPHORESIS is the motion of particles caused by a kind of thermally induced force, which arises from the non-uniform heating of particles due to temperature gradients in the suspending gas. Consider a particle suspended in the fluid with the temperature gradient. It is well known that gas molecules in a high temperature area have higher

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