Nonlinear absorption of surface plasmons and emission of electrons from metallic targets
D. B. Singh, Gagan Kumar, and V. K. Tripathi

Citation: Physics of Plasmas 14, 102108 (2007);
View online: https://doi.org/10.1063/1.2799173
View Table of Contents: http://aip.scitation.org/toc/php/14/10
Published by the American Institute of Physics

Articles you may be interested in
Anomalous absorption of surface plasma wave by particles adsorbed on metal surface
Nonlinear absorption of surface plasmons and emission of electrons from metallic targets

D. B. Singh
Laser Science and Technology Centre, Metcalfe House, Delhi-110054, India
Gagan Kumar and V. K. Tripathi
Department of Physics, Indian Institute of Technology, New Delhi-110016, India

(Received 18 June 2007; accepted 21 September 2007; published online 24 October 2007)

A large-amplitude surface plasma wave (SPW) over a metal-vacuum interface Ohmically heats the electrons and undergoes nonlinear absorption. The attenuation rate increases with the local SPW amplitude. The enhanced electron temperature leads to stronger thermionic emission of electrons. At typical Nd:glass laser intensity $I_L=7$ GW/cm$^2$, if one takes the amplitude of the SPW to be $\approx 6$ times the amplitude of the laser, one obtains the thermionic electron emission current density $J=200$ A/cm$^2$. However, the emission current density decreases with propagation distance at a much faster rate than the SPW amplitude and electron temperature. © 2007 American Institute of Physics. [DOI: 10.1063/1.2799173]

I. INTRODUCTION

Laser-induced heating and ablation of materials has been a subject of extensive study for quite some time. In the case of metallic targets, the efficiency of direct laser heating is poor as most of the energy is reflected back. The absorption of laser energy can be greatly enhanced when the laser gets mode-converted into surface plasmons (SP).1-5 This may be accomplished by using an attenuated total reflection (ATR) geometry,2 in which a metallic film is deposited on a glass prism and laser light falls obliquely on the glass metal interface, or by creating a suitable density ripple on the metal surface. The surface plasma wave acquires much larger amplitude than the laser and heats the electrons near the metal surface very efficiently. The heated electrons transfer energy to the lattice and cause melting, evaporation, and ablation of the material on a longer time scale. When the pulse duration is short, thermionic emission of heated electrons could be an important process. Many researchers6-10 have investigated surface plasmon enhanced electron emission at moderate laser intensity, $I_L \sim 1$ MW/cm$^2$, and obtained emitted electron current density of $J \sim 1$ mA/cm$^2$. Anisimov et al.11 studied thermionic emission of electrons at an absorbed laser flux density of $\sim 10^9-10^{10}$ W/cm$^2$ when pulse duration is short. With intense ultrashort pulse laser, one may achieve high current density,15 up to a few kA/cm$^2$. These pulsed emissions are useful in the development of high current high-voltage electron beams with wide-ranging application.15-16

One of the key issues at high power densities, however, is the nonlinear propagation of the surface plasma wave. The SPW suffers collisional absorption by electrons and the attenuation rate scales linearly with electron collision frequency that rises with electron temperature. Thus a high-amplitude SPW initially attenuates at a faster rate. As it loses power during propagation, its attenuation rate decreases.

In this paper, we study the nonlinear absorption of a large-amplitude surface plasma wave over a metal-vacuum interface and estimate enhanced electron emission from a metal surface. The physics of the phenomena is as follows. In the presence of SPW, electrons near the metal surface acquire oscillatory velocity $\bar{v}$ and undergo Ohmic heating. As the electron temperature rises nonuniformly, the electrons lose energy via collisions with the lattice and the thermal conduction. A quasi-steady-state is attained on a picosecond time scale when the energy-loss rate balances the heating rate. The electron temperature would increase with increasing SPW amplitude. Thus the SPW should suffer enhanced attenuation at higher intensities. The enhanced electron temperature should also manifest in stronger thermionic emission of electrons. In Sec. II, we study the nonlinear absorption of SPW over a metal surface. In Sec. III, we study the SPW induced emission of electrons. The results are discussed in Sec. IV.

II. NONLINEAR ABSORPTION OF SURFACE PLASMONS

Consider a metal-vacuum interface ($x=0$) with metal occupying half space $x<0$ and free space $x>0$. The metal is characterized by lattice permittivity $\varepsilon_L$, lattice temperature $T_0$, free-electron density $n_0$, electron effective mass $m$, and collision frequency $\nu$. The collision frequency depends on electron temperature $T_e$ as $\nu=\nu_0(T_e/T_0)^{1/2}$. A surface plasma wave propagates over the metal surface with electric field

$$\vec{E}=A_0\left(z+\frac{ik}{\alpha_I}\right)e^{-\alpha_Ix}e^{-i(k_{LZ}x)} \quad \text{for} \ \ x>0 \quad (1)$$

$$=A_0\left(z-\frac{ik}{\alpha_{II}}\right)e^{\alpha_{II}x}e^{-i(k_{LZ}x)} \quad \text{for} \ \ x<0, \quad (2)$$

where $\alpha_I=(k_L^2-\omega^2/c^2)^{1/2}$, $\alpha_{II}=(k_L^2-\varepsilon_m\omega^2/c^2)^{1/2}$, $k_L=(\omega/c)\sqrt{(\varepsilon_m/(1+\varepsilon_m))^{1/2}}$, $\varepsilon_m=\varepsilon_L-(\omega^2_0/\omega^2)^{1/2}(1-i\nu/\omega)$, and we have assumed $\nu^3 \ll \omega^3$. We may write

$\text{Electronic mail: dbsingh2@rediffmail.com}$
Defining the SPW amplitude $\beta$ depends on the SPW amplitude $A$.

The SPW amplitude may be defined as $A = A_0 e^{-k_z z}$ or

$$\frac{dA}{dz} = -k_z A. \quad (6)$$

Since $\nu$ depends on electron temperature $T_e$ and the latter depends on the SPW amplitude $A$, the attenuation constant $k_z$ is a function of $A$ and Eq. (6) is a nonlinear equation in $A$.

In order to obtain $k_z$ as a function of $A$, we examine the electron dynamics.

### Electron heating

The SPW field induces an oscillatory velocity on free electrons of the metal\(^1\)

$$\vec{v} = \frac{e\vec{E}}{m(\omega + i\nu)} \quad (7)$$

and heats them at the rate

$$R = -\frac{1}{2} \vec{v} \cdot \vec{E}^* \quad (8)$$

where * denotes complex conjugate. As the electron temperature $T_e$ rises above the lattice temperature $T_0$, the electrons lose energy to the lattice at the rate

$$R_1 = \frac{1}{2} \nu \Delta(T_e - T_0), \quad (9)$$

where $\Delta$ is the mean fraction of excess electron energy lost in a collision. The electrons also lose energy via thermal conduction at the rate

$$R_2 = \frac{d}{dx} \left( x \frac{dT_e}{dx} \right), \quad (10)$$

where $x = v_{th}^2 / \nu$ is electron thermal conductivity, and $v_{th} = (2T_e / m)^{1/2}$ is the electron thermal speed. In the steady state,

$$R = R_1 + R_2$$

or

$$-\frac{1}{2} \vec{v} \cdot \vec{E}^* = \frac{d}{dx} \left( \chi \frac{dT_e}{dx} \right) - \frac{3}{2} \nu \Delta(T_e - T_0) = 0. \quad (11)$$

Defining $\xi = (T_e / T_0)^{3/2}$, Eq. (11) can be written as\(^1\)

$$\frac{d^2 \xi}{dx^2} + \beta_1 \xi^{1/3} (\xi^{2/3} - 1) = \beta_2 \xi^{1/3} e^{-2\nu_{th} \xi^{2/3}}, \quad (12)$$

where

$$\beta_1 = \frac{9}{4} \frac{v_{th} \Delta}{\chi_{th}}, \quad \beta_2 = \frac{9}{4} \frac{c^2 v_{th}}{\nu_{th} \chi_{th}} \left( 1 + \frac{k_z^2}{\alpha_{th}^2} \right) \left( \frac{e}{moc} \right)^2,$$

$v_{th}$, $\chi_{th}$, and $v_{th}^0$ are the values of $\nu$, $\chi$, and $v_{th}$ at $T_e = T_0$.

In the narrow width $\sim 1/\alpha_{th}$, in which the SPW is localized at the metal-vacuum interface, one may take an average value of electron temperature. We may replace $d^2 \xi / dx^2 \equiv \langle \xi \rangle \alpha_{th}^2$. Then Eq. (12) takes the form

$$\langle \xi \rangle (\beta_1 + \alpha_{th}^2) - \beta_1 \langle \xi \rangle^{1/3} = \beta_2 \langle \xi \rangle^{1/3} A^2 / 2, \quad (13)$$

giving

$$\langle \xi \rangle = \left( \frac{\beta_2 A^2 / 2 + \beta_1}{\beta_1 + \alpha_{th}^2} \right)^{3/2} \quad (13)$$

Equation (13) gives the average electron temperature

$$\langle T_e \rangle = T_0 \left( \frac{\beta_2 A^2 / 2 + \beta_1}{\beta_1 + \alpha_{th}^2} \right)^{1/2} \quad (14)$$

With this temperature, the collision frequency can be written as

$$\nu = \nu_0 \left( \frac{\beta_2 A^2 / 2 + \beta_1}{\beta_1 + \alpha_{th}^2} \right)^{1/2} \quad (15)$$

and the attenuation constant as

$$k_z = k_{z0} \left( \frac{\beta_2 A^2 / 2 + \beta_1}{\beta_1 + \alpha_{th}^2} \right)^{1/2}, \quad (16)$$

where $k_{z0} = k_z(\nu = \nu_0)$. Using Eq. (16) in Eq. (6) and multiplying the resulting equation by $2A$, we obtain

$$\frac{dA}{dz} = -2k_{z0} \left( \frac{\beta_1}{\beta_1 + \alpha_{th}^2} \right)^{1/2} \left( 1 + \frac{\beta_2 A^2}{\beta_1^2} \right)^{1/2} A^2. \quad (17)$$

Defining $a = \beta_2 / 2\beta_1 A^2$, $k'_{z0} = k_{z0}(\beta_1 / \beta_1 + \alpha_{th}^2)^{1/2}$, this equation takes the form

$$\frac{da}{dz} = -2k'_{z0}(1 + a)^{1/2} a \quad (18)$$

giving

$$a = \frac{4C e^{-2a_{th}' z}}{(1 - C e^{-2a_{th}' z})^2}, \quad (19)$$

where

$$C = \frac{(1 + a_0)^{1/2} - 1}{(1 + a_0)^{1/2} + 1}, \quad a_0 = a(z = 0).$$

Taking the initial SPW amplitude as $A_0 = A(z = 0)$, we can write the SPW amplitude attenuation $A / A_0$ from Eq. (19) as

$$\frac{A(z)}{A_0} = \left( \frac{a}{a_0} \right)^{1/2} = \frac{2C^{1/2} e^{-k'_{z0} z}}{(1 - C e^{-2k'_{z0} z})^{1/2}}. \quad (20)$$

Similarly, from Eq. (14) we obtain the variation in average electron temperature with propagation distance as

$$\langle T_e(z) \rangle = \frac{1 + a(z)}{1 + a_0}, \quad (21)$$

where $\langle T_e(z) \rangle = \langle T_e \rangle(z = 0)$ is the initial average electron temperature.
We have plotted the normalized SPW amplitude $A/A_0$ as a function of propagation distance $z$ in Fig. 1 for different laser intensities $I_L$ taking the SPW field enhancement factor over the laser field to be 6 in ATR geometry at Nd:YAG laser frequency. The metal (silver) parameters are $\nu_0=2.3 \times 10^9 \omega_p$, $\varepsilon_L=3$, $\omega=0.13 \omega_p$, and $T_0=300 \text{ K}$. The wave damps more rapidly (i.e., the attenuation rate is higher) at higher laser intensity. In Fig. 1, we have plotted the normalized average electron temperature $\langle T_e \rangle / \langle T_{eo} \rangle$ with $z$. $\langle T_e \rangle / \langle T_{eo} \rangle$ decreases monotonically with $z$. At low values of $z$, where the SPW amplitude is large, the electron temperature decreases more rapidly. At higher laser intensity (i.e., higher SPW power density), the temperature decay rate is larger. All figures have been plotted in a semilog scale to reveal the decay rates in a better way.

**III. SPW INDUCED ELECTRON EMISSION**

The rate of thermionic emission of electrons per unit area per second can be obtained by the Richardson formula,

$$J = P \left( \frac{T_e}{k_B} \right)^2 e^{-\varphi/k_B T_e}, \quad (22)$$

where $P=120 \text{ A/cm}^2 / \text{K}^{-2}$, $\varphi$ is the work function of the metal (for noble metals gold and silver, $\varphi=4.3 \text{ eV}$), $k_B$ is Boltzmann’s constant having value $0.8617 \times 10^{-4} \text{ eV/K}$, $T_e$ is in electronvolts, and $J$ is the emission current density in $\text{A/cm}^2$. For a current density of $J=200 \text{ A/cm}^2$, one would require the electron temperature to be $T_e \sim 3000 \text{ K}$. The SPW induced electron heating would give rise to an emission current density that depends on electron temperature $T_e$ as given by Eq. (22). As the electron temperature decreases with the SPW propagation distance, the SPW induced emission current density would also decrease. Taking $J_0=J(z=0)$ as the initial current density, we obtain the normalized current density $J(z)/J_0$ as [from Eq. (22)]

$$J(z)/J_0 = \left( \frac{\langle T_e \rangle}{\langle T_{eo} \rangle} \right)^2 e^{-\varphi/(1/(\langle T_e \rangle)-1/(\langle T_{eo} \rangle)). \quad (23)$$

For the laser intensity $I_L=6.8 \text{ GW/cm}^2$, $T_0=300 \text{ K}$, $\omega=0.13 \omega_p$ (Nd:YAG laser), the current density at $z=0$ turns out to be $J_0=200 \text{ A/cm}^2$. In Fig. 3, we have plotted in a semilog scale the normalized value $J(z)/J_0$ and the absolute value $J(z)$ of the thermionic current density with distance $z$ for the silver parameters. The emission current density decreases with propagation distance at a much faster rate than the SPW amplitude and electron temperature. The current density decreases to about 10% of its initial value at a propagation distance of $z=50 \mu\text{m}$. This is due to the fact that the emission current density depends exponentially on the electron temperature.

**IV. DISCUSSION**

The surface plasmon assisted electron emission appears to be a potential scheme for generating ultrashort and intense electron pulses. The large-amplitude SPW could be excited by creating a suitable ripple on the metal surface or by depositing a metal film on a face of a prism in ATR geometry. Linear mode conversion theories indicate that one may easily achieve surface wave amplitude to incident laser amplitude ratio of the order of 6–10 at $1 \mu\text{m}$ laser wavelength in Au.
and Ag films. For typical parameters, one may achieve thermionic emission current densities \( \sim 200 \text{ A/cm}^2 \) at laser intensity \( \sim 7 \text{ GW/cm}^2 \) when the SPW to laser amplitude ratio is \( \approx 6 \). At higher SPW intensities, one may have material ablation on the metal surface. This laser intensity is two orders of magnitude smaller as compared to the one that is required if the laser has to directly heat the electrons to achieve the same electron emission current density.

The propagation vector of a surface plasma wave depends on the local SPW field. The attenuation rate, in particular, increases with SPW amplitude. Subsequently, the electron emission is nonuniform, being stronger at the input end of the SPW and weakens as the SPW propagates.