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Sputtering of metal atoms with the wake potential excited by an electron beam

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The process of metal atoms sputtering during a corona discharge is considered. When an electron moves in a medium at some velocity, charge screening occurs with a delay in space and time, which leads to the emergence of a wake potential. The excited oscillations of the wake charge lead to the appearance of additional forces. The energy loss of a moving particle per unit path is determined by the work produced of the deceleration force that acts on the particle from the side of the wake potential it creates in the medium. The paper considers the effect of the wake potential on the ions (atoms) sputtering of the lattice matrix. A well-known expression is used for the wake potential excited by a charged particle moving with energy, greater than the Fermi energy. An expression for the sputtering cross-section of metal atoms under the action of the wake potential excited by the electron beam is obtained. It is shown that the result of sputtering does not depend on the charge sign of the incident particle (electron or ion).

Keywords: corona discharge, nanoparticles, metal surface, inelastic scattering, wake potential.

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1. Introduction

The processes associated with electrical charges [1] are used in the state-of-the-art technologies because they allow to produce nanoscale components. At the same time, since components of even less size are required, corona discharge also have to be used because in this case components from units to fractions of nanometers can be obtained [2,3]. When corona discharge flows, atoms and molecules of the substance from which the electrodes are made get into gaseous fluid. Occurrence of a typical recess at the point of contact between the plasma core and electrode surface indicates on the presence of such evaporation [4].

This paper offers a theoretical metal sputtering model. It is shown that interaction of metal atoms (ions) with wakefield potential [5] excited by incident corona discharge electrons or ions is the cause of abnormal atom emission.

2. Wakefield potential excited by electrons moving in the substance

A charged fast particle flowing through the substance polarizes the substance molecules creating a variable dipole moment in each of them. Thus, polarization currents occur in the substance. The substance is excited by a fast charged particle through kinetic energy of the incident particle. If the excitation frequencies are of the same magnitude or lower than optical frequencies, then such excitations are long-wave and may be assessed in macroscopic electrodynamics [6]. In this case, excitations slowly damping with time, i.e. long-lived excitations, play the main role.

A homogeneous and isotropic medium can contain transverse electromagnetic waves whose wave vector $\mathbf{k}$ satisfies dispersion equation

$$k^2 - \left(\frac{\omega}{c}\right)^2 \varepsilon^{tr}(\mathbf{k}, \omega) = 0 \tag{1}$$

and longitudinal electromagnetic waves whose vector is determined by the following equations

$$\varepsilon^{l}(\mathbf{k}, \omega) = 0. \tag{2}$$

Permittivity vanishing is a prerequisite of longitudinal electromagnetic waves, i.e. wakefield charge [5] vibrations appear as a result of excitation of longitudinal electromagnetic waves by a moving charge.

For an electron moving in the medium at some velocity, the charge is screened with space and time delay leading to occurrence of a wakefield potential [5]. The wakefield charge density oscillations create the wakefield potential corresponding to this charge density. The Fourier transform equation for the wakefield charge is as follows

$$\Delta\varphi_{\omega}(\mathbf{r}, \omega) = -4\pi\rho_{\omega}(\mathbf{r}, \omega), \tag{3}$$

since the oscillation frequencies correspond to zeroes $\varepsilon^{l}(\mathbf{k}, \omega)$.

A field generated by the wakefield charge oscillations has an effect on an external particle and substance ions. Consider the wakefield charge oscillations corresponding

to a couple of zeroes $\varepsilon(\omega)$ to define the braking force related to this process. For a wide class of solid bodies, collective oscillations of substance electrons — plasmons, may exist. The oscillation frequency corresponds to permittivity vanishing

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma_p)}, \quad \omega_p^2 = \frac{4\pi n_e e^2}{m}. \tag{4}$$

(For metals, n_e corresponds to the number of conductivity electrons per unit volume.)

$\rho(\mathbf{r}, t)$ is an additional variable charge density generated in the substance as a result of the induced charge movement in the substance

$$\rho(\mathbf{r}, t) = \frac{ze\omega_p}{v} \sin\left\{\omega_p\left(t - \frac{z}{v}\right)\right\} \times \exp\left\{-\gamma_p\left(t - \frac{z}{v}\right)\right\} \delta(\boldsymbol{\rho})\theta(vt - z). \tag{5}$$

Thus, the wakefield charge oscillations excited by the field of external particles (incident electron or ion), that are not a part of the substance, generate additional forces. In particular, an incident free particle with charge Z_1 e at point $\mathbf{v}t$ at time t from the wakefield charge side generated by the same particle is exposed to force $\mathbf{F}(t) = -Z_1 e \operatorname{grad}\varphi(\mathbf{v}t, t)$.

Energy loss by the moving particle per unit path length is determined by the work of braking force acting on the particle from the electromagnetic field generated by the particle (wakefield potential) [6,7]:

$$\frac{dE}{dz} = \frac{\mathbf{vF}}{v} = \frac{Z_1 e}{v}(\mathbf{vE}) = -\frac{Z_1 e^2 4\pi n_e}{mv^2} \ln\left(\frac{vq_{\max}}{\omega_p}\right). \tag{6}$$

So, for the electron (ion) moving in the medium at some velocity, the charge is screened with space and time delay leading to occurrence of „the wakefield potential". For the electron (ion) moving in metal, screening and wakefield effect [7] are adequately described by the virtual plasmon excitation [5]. Neufeld and Ritchie [8] derived an expression for the wakefield potential for the charged particle moving with an energy higher than the Fermi energy:

$$\varphi = -\frac{2Z_1 e}{v}\omega_p \sin\left(\frac{\omega_p}{v} z\right) K_0\left(\rho\,\frac{\omega_p}{v}\right), \tag{7}$$

where $K_0\left(\rho\,\frac{\omega_p}{v}\right)$ is the modified Bessel function of the second kind, z and ρ are longitudinal and lateral coordinates. Potential energy of the lattice ion interaction with charge $Z_2 e$ may be written as follows

$$U(\rho, z) = Z_2 e\varphi = -\frac{2Z_1 Z_2 e^2}{v}\omega_p \sin\left(\frac{\omega_p}{v} z\right) K_0\left(\rho\,\frac{\omega_p}{v}\right). \tag{8}$$

Vager and Gemmel [9] offered the following wakefield charge equation:

$$\varphi(\rho, z - \omega t) = -\frac{Z_1 e\omega_p}{v}\int_0^\infty \sin\left(\frac{\omega_p}{v}\xi\right) \times \left[\rho^2 + \left(\frac{\hbar}{mv}\right)^2 + (\xi + z - vt)^2\right]^{-1/2} d\xi. \tag{9}$$

In [10], a wakefield potential equation written through permittivity was offered

$$\varphi = -\frac{Z_1 e}{\pi v}\int_0^\infty \xi d\xi J_0(\xi\rho) \times \int_{-\infty}^{\infty} d\omega \exp\left(\frac{i\omega(z - vt)}{v}\right)\frac{1}{k^2}\,\frac{1}{\varepsilon(k, \omega)}, \tag{10}$$

where $\rho = (x^2 + y^2)^{1/2}$ and $k^2 = \xi^2 + \frac{\omega^2}{v^2}$.

From expression (10), the Neufeld and Ritchie equation may be derived (7). If $\frac{1}{\varepsilon(k,\omega)} = i\pi\delta\big(\varepsilon(k, \omega)\big)$ [6] and permittivity is in the form of (4), then integration for $d\omega$ gives the following expression

$$\varphi = -\frac{Z_1 e}{2v} i\int_0^\infty \xi d\xi J_0(\xi\rho)\omega_p \exp\left(\frac{i\omega_p(z - vt)}{v}\right)\frac{1}{\xi^2 + \omega_p^2/v^2} = -\frac{Z_1 e}{2v}\omega_p K_0\left(\frac{\omega_p}{v}\rho\right)\sin\left(\frac{\omega_p(z - vt)}{v}\right)\theta(vt - z), \tag{11}$$

which coincides with Neufeld's and Ritchie's result (7).

3. Metal ion sputtering by wakefield potential

Now consider the wakefield potential effect on the lattice matrix ions (atoms). For the electron (ion) moving in metal, screening and wakefield effect [7] are adequately described by the expression (11). For an ion (atom) of the target substance, transition probability at unit time to the first perturbation theory approximation [11]:

$$dP_{fi} = \frac{2\pi}{\hbar}\left|\left\langle\Phi_f^*|W|\Phi_i\right\rangle\right|^2 \frac{mk_f d\Omega}{(2\pi\hbar)^2}, \tag{12}$$

where the matrix element is defined by the following integral

$$\left\langle\Phi_f^*|W|\Phi_i\right\rangle = \int \varphi_f^*(\xi)W(\mathbf{r}, \xi)\varphi_i(\xi)d\xi \exp\big(i(\mathbf{k}_i - \mathbf{k}_f)\mathbf{r}\big)d^3\mathbf{r},$$

where $W(\mathbf{r}, \xi) = -\mathrm{Im}\,\frac{Z_1 e}{2v}\omega_p K_0\big(\frac{\omega_p}{v}\rho\big)\exp\big(\frac{\omega_p(z - v\xi)}{v}\big)$ is the interaction operator (8), $\varphi_f(\xi)$ and $\varphi_i(\xi)$ are wave functions of the final and initial ion states in the lattice. Integral for $d\xi$ is as follows

$$\int_0^\infty \exp\left(i\varepsilon_b\xi + i\,\frac{p_i^2}{2m}\xi\right)\exp\left(-i\omega_b\xi - i\,\frac{p_f^2}{2m}\xi\right) = 1/2\ \delta\left(\omega_p + \frac{p_f^2}{2m} - \varepsilon_b + \frac{p_i^2}{2m}\right), \tag{13}$$

where ε_b is the in bond energy in the lattice of the material.

Effective cross-section of (elastic and inelastic) scattering to the first Born approximation may be written as follows:

$$d\sigma_{fi}^{(Bohr)} = \left(\frac{m}{2\pi\hbar^2}\right)^2 \frac{p_f}{p_i} \left|\left\langle \Phi_f^* | W | \Phi_i \right\rangle\right|^2 d\Omega, \qquad (14)$$

where $p_f = \sqrt{p_i^2 + 2m(\omega_p - \varepsilon_b)}$.

For calculation of the total cross-section, use a quasiclassical expression for the optical theorem [12]:

$$\sigma_{tot} = 4\pi \int_0^\infty \rho d\rho \left\{ 1 - \cos\left[\frac{1}{\hbar v} \int_{-\infty}^{\infty} U(\sqrt{\rho^2 + z^2}) dz\right]\right\}$$

$$\approx 2\pi \int_0^\infty \rho d\rho \, \frac{1}{(\hbar v)^2} \left[\int_{-\infty}^{\infty} U(\sqrt{\rho^2 + z^2}) dz\right]^2. \qquad (15)$$

Using the epression (8) for the interaction potential

$$U(\rho, z) = Z_2 e\varphi = -\frac{2Z_1 Z_2 e^2}{v} \omega_p \sin\left(\frac{\omega_p}{v} z\right) K_0\left(\rho \frac{\omega_p}{v}\right),$$

after introduction of dimensionless integration variables, we obtain

$$\sigma_{tot} \approx \frac{\pi}{2} \frac{1}{(\hbar\omega_p)^2} Z_1^2 Z_2^2 e^4 \int_0^\infty x dx \left(\int_0^\infty K_0\left(\sqrt{x^2 + \xi^2}\right) \sin\xi d\xi\right)^2. \qquad (16)$$

Thus, the total sputtering cross-section with an accuracy to the numerical factor is proportional to

$$\sigma_{tot} \sim \frac{1}{(\hbar\omega_p)^2} Z_1^2 Z_2^2 e^4 \theta(\hbar\omega_p - \varepsilon_b). \qquad (17)$$

The obtained expression means that the sputtering result is not sensitive to the sign of the incident particle (electron or ion).

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Conflict of interest

The author declares that he has no conflict of interest.

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