Available online at www.sciencedirect.com

SCIENCE DIRECT

Nuclear Instruments and Methods in Physics Research B 243 (2006) 293–298

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Memory effect on energy losses of charged particles moving parallel to solid surface

C.M. Kwei [a,*], Y.H. Tu [a], Y.H. Hsu [a], C.J. Tung [b]

[a] Department of Electronics Engineering, National Chiao Tung University, Hsinchu 300, Taiwan
[b] Department of Nuclear Science, National Tsing Hua University, Hsinchu 300, Taiwan

Received 16 June 2005; received in revised form 22 August 2005
Available online 26 October 2005

Abstract

Theoretical derivations were made for the induced potential and the stopping power of a charged particle moving close and parallel to the surface of a solid. It was illustrated that the induced potential produced by the interaction of particle and solid depended not only on the velocity but also on the previous velocity of the particle before its last inelastic interaction. Another words, the particle kept a memory on its previous velocity, v_0, in determining the stopping power for the particle of velocity v. Based on the dielectric response theory, formulas were derived for the induced potential and the stopping power with memory effect. An extended Drude dielectric function with spatial dispersion was used in the application of these formulas for a proton moving parallel to Si surface. It was found that the induced potential with memory effect lay between induced potentials without memory effect for constant velocities v_0 and v. The memory effect was manifest as the proton changes its velocity in the previous inelastic interaction. This memory effect also reduced the stopping power of the proton. The formulas derived in the present work can be applied to any solid surface and charged particle moving with arbitrary parallel trajectory either inside or outside the solid.

PACS: 78.20.Bh; 78.70.−g

Keywords: Memory effect; Surface excitation; Inelastic interaction

1. Introduction

When a charged particle moves close and parallel to the surface of a solid, induced potential is produced due to the interaction of particle and solid. This potential is then acted on the particle resulting to a stopping power. Theoretical derivations of the induced potential and the stopping power were previously made [1–4] for a constant velocity, v_0, of the particle until it experienced an inelastic interaction. After the interaction, the particle changed its velocity to v and continued to interact with the solid. For a second inelastic interaction, it was generally assumed that a new induced potential, dependent only on v but not on v_0, was generated. This new potential then determined the stopping power acting on the particle of velocity v. In the present work, the induced potential and stopping power for the second inelastic interaction were derived using image charges and dielectric response functions. It was found that the particle previous velocity v_0 had also an effect on the second inelastic interaction. Another words, the particle kept a memory on its previous velocity, v_0, in determining the stopping power for the particle of velocity v.

The response of solid to a charged particle moving close and parallel to the surface may be characterized by its surface loss-function, $\text{Im}[-1/(\varepsilon+1)]$, where ε is the dielectric function of the solid and Im[ ] denotes the imaginary part. A sum-rule-constrained extended Drude dielectric function with spatial dispersion [5] was established with parameters determined from optical data. Previously, this dielectric

* Corresponding author. Tel.: +886 3 5712121x54136; fax: +886 3 5727300.
E-mail addresses: cmkwei@mail.nctu.edu.tw, cmkwei@cc.nctu.edu.tw (C.M. Kwei).

0168-583X/$ - see front matter
doi:10.1016/j.nimb.2005.08.186

function was applied to the interface [6–8] and overlayer systems [3,9,10] for a charged particle without memory effect. With the consideration of memory effect, we applied this dielectric function in this work. The induced potential was then derived by solving Poisson equations in Fourier space by a method of image charges which satisfied the boundary conditions. The stopping power was then constructed from the derivative of the induced potential at particle position. Calculations were made using these formulas for a proton moving parallel to Si surface. Results were analyzed for the dependences of the induced potential and stopping power on proton velocities before and after the last inelastic interaction, the distance from surface, and the distance from previous inelastic interaction. Finally, the calculated results with memory effect were compared with the corresponding results without memory effect.

2. Theory

Fig. 1 illustrates the problem studied in the present work. A particle of charge q, velocity $\vec{v}_0$ and energy E_0 moves parallel to the interface of two media of dielectric functions $\varepsilon_1(\vec{k},\omega)$ and $\varepsilon_2(\vec{k},\omega)$. The interface is located at $z = 0$, with z-axis perpendicular to the interface plane and directed from $\varepsilon_1(\vec{k},\omega)$ to $\varepsilon_2(\vec{k},\omega)$. The particle is moving along y-direction at a distance D above the interface. At the moment $t = 0$, the particle experiences an inelastic interaction which changes particle velocity and energy to $\vec{v}$ and E. Assuming the particle continues to move along the same direction, the induced potential at $t > 0$ is of special interest here. For $z > 0$, the scalar potential is produced by the particle and a fictitious charge at $z < 0$ near the interface. For

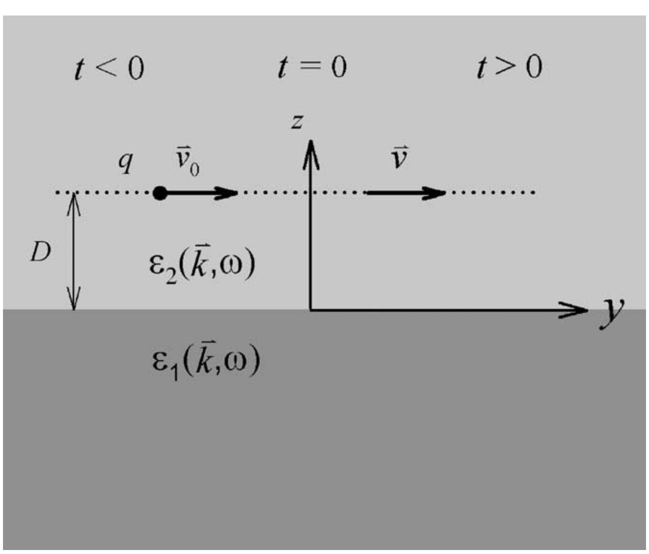

Fig. 1. A sketch of the problem studied in the present work. A particle of charge q, velocity $\vec{v}_0$ moves parallel to the interface of two media of dielectric functions $\varepsilon_1(\vec{k},\omega)$ and $\varepsilon_2(\vec{k},\omega)$. The interface is located at $z = 0$ and the particle is moving along y-direction at a distance D above the interface. At time $t = 0$, the particle experiences an inelastic interaction which changes particle velocity to v. Special interest is on the induced potential and the stopping power at $t > 0$.

$z < 0$, the potential is produced by a fictitious charge at particle position and by another fictitious charge at $z > 0$ near the interface. These fictitious charges should be established using boundary conditions that are satisfied at the interface. Thus the Poisson equations in Fourier space are

$$\varphi_1(\vec{k},\omega) = \frac{4\pi}{k^2\varepsilon_1(\vec{k},\omega)}\left[\rho(\vec{k},\omega) + \rho_{\mathrm{f}}(\vec{Q},\omega)\right] \quad (1)$$

for $z < 0$ and

$$\varphi_2(\vec{k},\omega) = \frac{4\pi}{k^2\varepsilon_2(\vec{k},\omega)}\left[\rho(\vec{k},\omega) - \rho_{\mathrm{f}}(\vec{Q},\omega)\right] \quad (2)$$

for $z > 0$, where $\vec{k} = (k_x, k_y, k_z) = (\vec{Q}, k_z)$ is the momentum transfer and ω is the energy transfer. The Fourier transform of the charge density distribution of the particle

$$\rho(\vec{r},t) = q\delta(x)\delta(z-D)[\delta(y-v_0t)\Theta(-t) + \delta(y-vt)\Theta(t)] \quad (3)$$

is given by

$$\rho(\vec{k},\omega) = q\mathrm{e}^{-\mathrm{i}k_zD}\left[\int_{-\infty}^{0}\mathrm{e}^{\mathrm{i}(\omega-k_yv_0)\tau}\mathrm{d}\tau + \int_{0}^{\infty}\mathrm{e}^{\mathrm{i}(\omega-k_yv)\tau}\mathrm{d}\tau\right], \quad (4)$$

where $\delta()$ and $\Theta()$ are the delta- and step-functions, respectively. To satisfy the boundary conditions at the interface, the fictitious charge in Fourier space is given by

$$\rho_{\mathrm{f}}(\vec{Q},\omega) = \frac{\int_{-\infty}^{\infty}\frac{\rho(\vec{k},\omega)}{k^2}\left[\frac{1}{\varepsilon_2(\vec{k},\omega)} - \frac{1}{\varepsilon_1(\vec{k},\omega)}\right]\mathrm{d}k_z}{\int_{-\infty}^{\infty}\frac{1}{k^2}\left[\frac{1}{\varepsilon_2(\vec{k},\omega)} + \frac{1}{\varepsilon_1(\vec{k},\omega)}\right]\mathrm{d}k_z}. \quad (5)$$

Combining Eqs. (4) and (5), one gets

$$\rho_{\mathrm{f}}(\vec{Q},\omega) = q\left[\int_{-\infty}^{0}\mathrm{e}^{\mathrm{i}(\omega-k_yv_0)\tau}\mathrm{d}\tau + \int_{0}^{\infty}\mathrm{e}^{\mathrm{i}(\omega-k_yv)\tau}\mathrm{d}\tau\right] \times \left[\frac{\frac{1}{\bar{\varepsilon}_2(D,\vec{Q},\omega)} - \frac{1}{\bar{\varepsilon}_1(D,\vec{Q},\omega)}}{\frac{1}{\bar{\varepsilon}_2(\vec{Q},\omega)} + \frac{1}{\bar{\varepsilon}_1(\vec{Q},\omega)}}\right], \quad (6)$$

where the effective dielectric function is given by

$$\frac{1}{\bar{\varepsilon}_L(D,\vec{Q},\omega)} = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{\mathrm{e}^{-\mathrm{i}k_zD}}{k^2\varepsilon_L(\vec{k},\omega)}\mathrm{d}k_z \quad (7)$$

for $L = 1$ and 2 and $\bar{\varepsilon}_L(\vec{Q},\omega) = \bar{\varepsilon}_L(0,\vec{Q},\omega)$.

Substituting Eqs. (4)–(7) into Eqs. (1) and (2), one obtains the scalar potentials in Fourier space, i.e. $\varphi_1(\vec{k},\omega)$ and $\varphi_2(\vec{k},\omega)$. The induced potentials in Fourier space, $\varphi_1^{\mathrm{ind}}(\vec{k},\omega)$ and $\varphi_2^{\mathrm{ind}}(\vec{k},\omega)$, are then obtained by removing the vacuum potential of the particle from scalar potentials. One gets

$$\varphi_1^{\mathrm{ind}}(\vec{k},\omega) = \frac{4\pi}{k^2}\left(\frac{1}{\varepsilon_1(\vec{k},\omega)} - 1\right)\rho(\vec{k},\omega) + \frac{4\pi}{k^2\varepsilon_1(\vec{k},\omega)}\rho_{\mathrm{f}}(\vec{Q},\omega) \quad (8)$$