Local versus nonlocal description of the energy loss of electrons via plasmon excitation backscattering from solid surfaces

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The differences between the local and nonlocal descriptions of the energy loss of electrons backscattered from a Si surface, focusing on surface and bulk plasmon excitations, are studied quantitatively in the present work. Beyond the usually applied "V-shape" electron trajectories, calculations have done for realistic electron trajectories derived by Monte Carlo simulation even in the case of nonlocal description of the electron-energy-loss process. It allowed to perform the detailed investigation of the effects of the interference (i.e., the interaction of the electron with the electric field induced at the earlier stage of its trajectory) in case of real electron trajectories. It is clearly shown that significant interference effects occur only in the case of surface plasmon excitations, however, these are less pronounced than predicted by the simple V-shape trajectory approximation. Furthermore, it is pointed out that the error caused by neglecting interference effects in the case of the local description of electron energy losses through collective excitations in the near-surface region of the solid is less than 6.2% when the primary electron energy is higher than 500 eV. As a consequence, the application of Monte Carlo simulation techniques based on a local description of the electron-energy-loss process is possible at these primary electron energies in order to the fast modeling of the complete near-surface electron-transport process (including inelastic and elastic electron scattering) without significant errors due to the neglect of the interference effects.

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I. INTRODUCTION

Detailed knowledge and accurate description of electron-transport processes have a crucial importance for fundamental studies of electron-solid interactions as well as for applications of surface analytical techniques (x-ray photoemission spectroscopy, angle-resolved x-ray photoemission spectroscopy, x-ray excited Auger electron spectroscopy, reflected electron energy loss spectroscopy, transmission electron microscopy, and scanning electron microscopy). The most probable electron-solid interaction, resulting in electron energy loss within a solid medium, is the collective excitation of the free or nearly free electrons of the solid, i.e., the plasmon excitation. The nature of these charge-density fluctuations in the near-surface region of the solid is different from those taking place deeply inside the solid, due to the presence of the solid-vacuum boundary.[1–3] Since a significant portion of the transport of medium and low-energy electrons takes place in the near-surface region of solid the effects from this boundary must be taken into account for the accurate modeling of the electron-transport processes in solids. The theoretical models[4–15] developed in the past half century to describe both bulk and surface plasmon excitations are based on two fundamentally different approaches.

One group of theories[4–10] describes the plasmon excitation processes as successive, completely independent events. This means that the actual energy loss of the electron depends only on the actual position and velocity vector of the electron and the past history does not have any influence on the actual energy loss process. The energy loss of the electron is handled as a *local* process. In this case of theories, the plasmon excitations are assumed to be a Markovian, i.e., a clear stochastic process. The so-called interference effect, defined as the interaction of the electron with the electric field induced at the earlier stages of its trajectory is not considered in the case of theories based on the local description of the electron-energy-loss process. It should be noted that this interference effect is a classical electrodynamic interference effect instead of the well-known quantum-mechanical interference.

Contrary to the local descriptions, the effects of this interference are taken into account in the case of the second group of theories making these descriptions of the electron energy loss through plasmon excitations *nonlocal*. The energy loss process of the electron is described as a nonlocal process in the case of these theories considering the interaction of the electron with the electric fields induced by itself at the earlier stage of its trajectory, assuming a physically more complete picture compared to the *local* descriptions.

The Monte Carlo simulation of the electron-transport processes is the most convenient technique in the case of stochastic (local) description of the electron energy loss (without interference effect) in solids, accounting accurately for the stochastic nature of the elastic electron scattering as well (in the case of amorphous samples), beyond the electron-solid interactions resulting in an energy loss of the projectile.[16–19] The entire transport process is handled as a stochastic process in this case.

On the other hand, the description of the electron-energy-loss processes along an arbitrary electron trajectory is considerably complicated using nonlocal theoretical models (including interference effects) due to their complexity and the necessity of the preliminary information on the electron trajectories. Consequently, most of these models are considering only special, unrealistic electron trajectories where the effect of the elastic scattering of electrons is ignored or taken into account at a low level (straight line or V-shape trajectory approximation).[11–14] Beyond the complications originating

from the necessary information to be provided for the calculations regarding the electron trajectories the nonlocal descriptions of the electron energy loss is rather time consuming since the calculations are longer (by several order of magnitudes) compared to the case of local descriptions. Furthermore it should be noted that the first-principles quantum-mechanical treatment of the energy losses of electrons backscattered from solid surfaces has been worked out by Nazarov[20,21] in the case of electrons suffered a single inelastic event.

Due to these facts the missing information on the magnitude of the differences between the local and nonlocal descriptions of the electron-energy-loss process has a crucial importance in modeling the electron transport in solids. This lacking information can help to decide which description is the appropriate (regarding the computation time and the desirable accuracy) for describing and modeling the electron-transport processes in a given situation.

The differences between the local and nonlocal descriptions of the average energy lost by the backscattered electron through plasmon excitations are investigated quantitatively in the present work using the theory developed by Vicanek.[10] Furthermore, the average energy loss of electrons (caused by surface and bulk plasmon excitations) backscattered from a Si sample has been calculated assuming V shape electron trajectories as well as realistic electron trajectories derived by a Monte Carlo simulation. The results of the different theoretical approximations describing the energy loss process (local and nonlocal descriptions) as well as the different assumptions on the electron trajectories (V shape and real trajectories) have been compared. All this missing information influences the applicability of effective Monte Carlo techniques in modeling the near-surface transport of medium- and low-energy electrons based on the stochastic description of both elastic and inelastic events.

II. THEORY

Vicanek[10] has developed both local and nonlocal theories to describe the average energy loss of the backscattering electron through collective excitations in the near-surface region of solids based on dielectric response theory. The details of these theories are described elsewhere only the most relevant formulae (applied in the present work) are presented here.

The surface plasmon frequency is given as $\omega_S=(\omega_0^2/2-\gamma^2)^{1/2}$ assuming that the dielectric function of the sample has the form[10]

$$\frac{1}{\varepsilon(\omega)} = 1 + \frac{\omega_0^2}{\omega^2 + 2i\gamma\omega - \omega_0^2}, \tag{1}$$

where ω_0 and γ are the plasma resonance frequency and the damping rate, respectively. The accurate values of these parameters can be derived through the fit of the imaginary part of Eq. (1) to the same quantity calculated from the measured optical data.[22,23] It should be noted that nonlocality in time and locality in space are already introduced choosing the dielectric function of the form given in Eq. (1) through its frequency dependence and due to the fact that the spatial dispersion is neglected in Eq. (1). It means that the local model of the electron transport (defined in the introduction part) contains nonlocality in time as well as the nonlocal model of the electron transport (defined in the introduction part) contains some locality in space in Vicanek's theory[10] due to the approximation of the dielectric function of the sample according to Eq. (1). In other words, Vicanek, in spite of using a nonlocal model of the transport, for simplicity only considered a local approximation for the dielectric susceptibility of the solid.

Choosing the dielectric function of the sample according to Eq. (1) the following expressions were derived by Vicanek for the depth (z) dependent bulk [Eq. (2)] and surface [Eq. (3)] stopping power of the electrons, in the local approximation of the electron energy loss via collective excitations[10]

$$\left.\frac{dW}{dx}\right|_B = \frac{2\omega_0}{\pi v}\int_0^{K_C}\frac{dk}{k}\int_0^{\infty} dt\,\exp(-\gamma t)[\omega_0\cos(\omega_0 t) - \gamma\sin(\omega_0 t)]\left[\frac{\sin(kvt)}{vt} - \frac{\sin(k\sqrt{4z^2+v^2t^2})}{\sqrt{4z^2+v^2t^2}}\right] \tag{2}$$

$$\left.\frac{dW}{dx}\right|_S = \frac{2\omega_S}{\pi v}\int_0^{K_C}\frac{dk}{k}\int_0^{\infty} dt\,\exp(-\gamma t)[\omega_S\cos(\omega_S t) - \gamma\sin(\omega_S t)]\frac{\sin(k\sqrt{4z^2+v^2t^2})}{\sqrt{4z^2+v^2t^2}}, \tag{3}$$

where v is the velocity of the electrons, $K_C=\omega_0/v_F$ is the cut-off wave number[24] and v_F is the Fermi velocity.

Using a nonlocal description of the energy loss process of the electrons caused by collective excitations Vicanek derived the following expressions for the average energy lost by the backscattered electrons through surface and bulk plasmon excitations after traveled along the path $\vec{r}=\vec{R}(t)$

$$W_B = -\int_{t_O}^{t_I} dt\int_{t_O}^{t} dt'\,\dot{\varphi}_B(\vec{R},\vec{R}',t-t') \tag{4}$$

$$W_S = -\int_{-\infty}^{\infty} dt\int_{-\infty}^{t} dt'\,\dot{\varphi}_S(\vec{R},\vec{R}',t-t'), \tag{5}$$

where $\varphi(\vec{r},\vec{R},t)$ represents the potential at time t and position $\vec{r}$ induced by a unit point charge that flashes up at time $t=0$ and position $\vec{R}$. The notations t_0 and t_1 denote the time of entrance and escape of the electrons, respectively. Vicanek derived the following expressions for the φ_S and φ_B using the same model dielectric functions as applied in the previous case [Eq. (1)][10]

$$\varphi_S(\vec{r},\vec{R},t) = -\frac{\omega_0^2}{2\omega_S}\exp(-\gamma t)\sin(\omega_S t)\begin{cases} 1/|\vec{r}-\vec{R}| & \text{if } zZ<0 \\ 1/|\vec{r}-\vec{\bar{R}}| & \text{if } zZ>0, \end{cases} \tag{6}$$

where $\vec{\bar{R}}=(X,Y,-Z)$ is the position of the image charge and for bulk excitations

$$\varphi_B(\vec{r},\vec{R},t) = \varphi_{\text{inf}}(\vec{r}-\vec{R},t) - \varphi_{\text{inf}}(\vec{r}-\vec{\bar{R}},t) \text{ if } z>0; Z>0 \tag{7}$$

$$\varphi_{\text{inf}}(\vec{r},t) = -\frac{2\omega_0^2}{\pi\omega_0' r}\text{Si}(K_C r)\sin(\omega_0' t)\exp(-\gamma t), \tag{8}$$

where $\text{Si}(x)=\int_0^x \sin(t)/t\,dt$ is the sine integral and $\omega_0' = \sqrt{\omega_0^2-\gamma^2}$.

Note that contrary to the local description of the electron energy lost in collective excitations [Eqs. (2) and (3)] the interaction of the electron with the electric field induced at the earlier stage of its trajectory, i.e., the interference effect, is taken into account in the case of the nonlocal description [Eqs. (4) and (5)]. In addition, surface excitations, as well as the depth dependence of the probability of surface and bulk excitations, are taken into account at both sides of the solid-vacuum interface in both theories. Furthermore, the nonlocal description presented here is able to calculate the average energy lost by the backscattered electrons for arbitrary trajectories $\vec{r}=\vec{R}(t)$ providing an opportunity for investigating the interference effects even in the case of real electron trajectories which is the uniqueness of the present work.

III. RESULTS AND DISCUSSION

The primary energy of electrons was chosen to be high enough to apply quasielastic Monte Carlo technique[18] for simulating real electron trajectories and low enough to keep the trajectories localized in both space and time. The value of inelastic mean-free path and elastic mean-free path decrease the electron energy. The lower-energy electrons are backscattered from a shallower region of the sample ensuring that the incoming and outgoing parts of the electron trajectories are close to each other regarding both space and time. The effect of interference is expected to be higher in this lower energy case as predicted by Pauly *et al.*[25] using V-shape trajectories. On the other hand, the quasielastic Monte Carlo approach was applied to obtain realistic electron trajectories accounting for the elastic scattering process of electrons accurately during the transport.[18] Within this approximation it is assumed that the elastic scattering process is responsible exclusively for changes in the direction of the traveling electron (in the case of amorphous samples). Furthermore it is assumed that the energy lost by the electron in a given excitation event is low compared to the primary energy of the electron so the values of the parameters governing the transport do not change significantly, therefore, constant values can be used during the simulation procedure. These assumptions are less valid when decreasing the kinetic energy of the electron, i.e., the primary energy of the electrons must be high enough to keep this assumption valid. The primary energy of the electrons was chosen to be 500 eV to satisfy all the requirements mentioned above.

The backscattered electrons were detected in the direction of the surface normal and the angle of the incoming electron beam (α) varied between 0° and 85° with respect to the surface normal. The average energy loss of the electrons via surface and bulk plasmon excitations was calculated in the case of electrons backscattered from a Si ($\omega_0=0.617; \gamma=0.075; K_C=0.64$) surface using a primary electron energy of 500 eV ($v=6.062$) by means of the integration of the stopping power along the individual electron trajectories [Eqs. (2)–(5)]. Both local (surface excitations: see Fig. 1) and nonlocal (surface excitations: see Fig. 2) approaches of the electron-energy-loss process were applied. The calculations were carried out for realistic electron trajectories derived by Monte Carlo simulation (dots) as well as using the V-shape trajectory approximation (lines).

The probability of surface excitation converges to zero rapidly increasing the depth inside the sample (15–20 Å at the given electron energy).[8–10] This is the reason why the average energy loss caused by surface excitations reaches a constant value for trajectories with a maximum depth higher than 15–20 Å in the case of the straight-line approximation (see Fig. 1). When the surface crossing angle (α) is higher, the electron travels a longer path in the surface-excitation region, consequently its energy loss caused by surface excitations is higher (see Figs. 1 and 2). The V-shape trajectory approximation is the shortest possible path in the case of $\alpha=0°$ to reach the given value of the maximum depth. The elastic scattering of electrons makes the real trajectories random walklike governed by the differential elastic electron scattering cross sections. As a consequence, the electrons travel a realistic, longer zigzag path in the surface excitation region (as well as inside the solid) in case of $\alpha=0°$ and both longer and shorter paths are possible in the surface excitation region (as well as inside the solid) in the case of α values higher than predicted by the V-shape trajectory approximation. Accordingly, the dots correspond to the real trajectories scatter around the results derived by using the V-shape trajectory approximation (see Fig. 1).

This effect due to elastic electron scattering is more important in the case of the nonlocal approach to the electron energy loss by plasmon excitations (see Fig. 2). A strong oscillation feature is observable in the average energy loss caused by surface plasmon excitations as a function of the maximum depth reached by the electron in the case of using V-shape trajectory approximation. These oscillations are more pronounced in the case of low α values and of maximum depth where the incoming and outgoing parts of the electron trajectories are overlapping regarding both space and time. The oscillations are attributable to the interference effects.[10,12,15,25] The outgoing electron interacts with the electric field induced in the sample by itself at the earlier stage of its trajectory and the nature of the charge-density oscillations induced along the trajectories of the outgoing electrons are influenced by those induced on the incoming part of the trajectories. Although, this effect has been reported earlier by other groups using unrealistic straight-line approximations,[10,12,15] its detailed investigation and the mag-

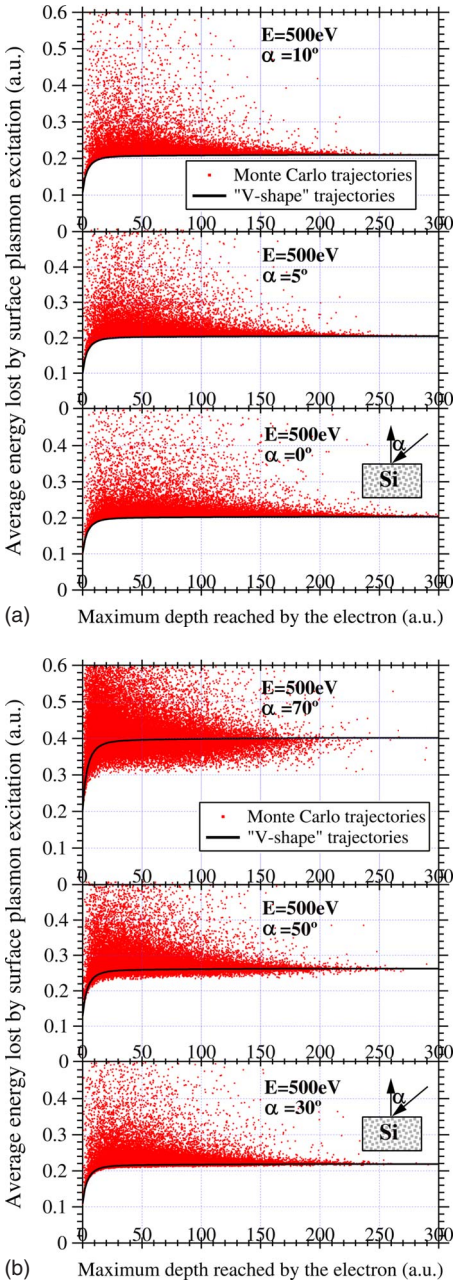

FIG. 1. (Color online) (a) Average energy loss of 500 eV primary energy electrons backscattered from a Si surface due to surface plasmon excitations, as a function of the maximum depth reached by the electrons inside the sample in the case of local description of the energy loss process. Both realistic electron trajectories (dots) and "V-shape" trajectory approximation (line) were applied. The electrons were detected in the direction of the surface normal and the angles of the incoming electron beam were 0°, 5°, and 10° with respect to the surface normal. (b) Same as in Fig. 1(a) in the case of angles of 30°, 50°, and 70° of the incoming electron beam with respect to the surface normal.

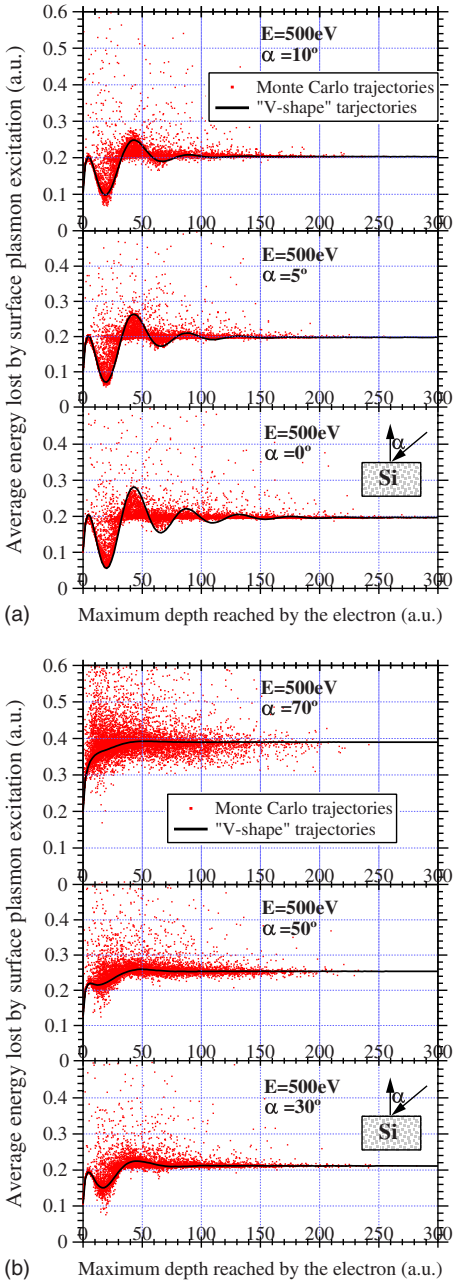

FIG. 2. (Color online) (a) Same as in Fig. 1(a) using nonlocal description of the energy loss process. (b) Same as in Fig. 1(b) using nonlocal description of the energy loss process.

nitude of its influence to the electron-transport modeling have not been investigated up till now in the case of realistic electron trajectories considering the elastic scattering appropriately. It should be noted, that the interference effect has recently been investigated by Pauly *et al.*[25] co-workers using V-shape trajectory approximation that provides unrealistic electron trajectories. Beyond the results of the V-shape trajectory approximation, Fig. 2 shows the values derived for the average energy loss caused by surface plasmon excitations in the case of real electron trajectories (dots) as well. One can see that the oscillations are less pronounced in the case of real electron trajectories (as predicted already by Vicanek)[10] compared to those appeared in the results derived by using V-shape trajectory approximation. This is attributable to the smaller overlap of the incoming and outgoing trajectories in the real case due to the elastic electron scattering. The oscillation disappears in both cases of trajectories when increasing the incoming angle and/or in the case of

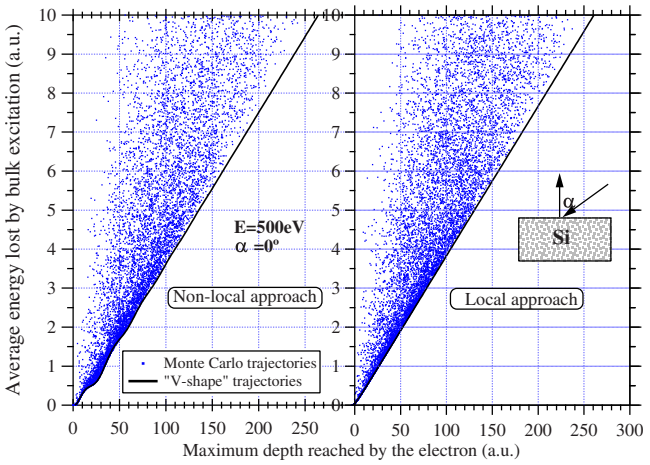

FIG. 3. (Color online) Average energy loss of 500 eV primary energy electrons backscattered from a Si surface due to bulk plasmon excitations, as a function of the maximum depth reached by the electrons inside the sample, applying nonlocal and local descriptions of the energy loss process. Both realistic electron trajectories (dots) and "V shape" trajectory approximation (line) were applied. The electrons were detected in the direction of the surface normal and the angle of the incoming electron beam was 0° with respect to the surface normal.

trajectories penetrating deeper inside the solid, again due to the smaller overlap of the incoming and outgoing trajectories regarding both space and time.

The rate of the oscillations, appearing in the average energy lost by the electron in surface plasmon excitations as a function of the maximum depth reached, is comparable to the average of this value when the value of α is low enough. Contrarily, this oscillating feature is negligible in the case of the average energy lost by the electron in bulk plasmon excitations, even when using the straight-line trajectory approximation and totally overlapping electron trajectories (α $=0°$) as it is shown in Fig. 3.

This phenomenon is attributable to the fact that the magnitude of the oscillations caused by the interference effect is insignificant compared to the average energy lost by the electrons in bulk excitations along their trajectories. Furthermore, this small difference completely disappears in the case of using realistic, less overlapping (regarding space and time) trajectories (dots) due to the zigzag nature of the real trajectories as a result of the elastic scattering of the electrons. Therefore the interference has a significant effect only on the average energy lost by the electron through surface plasmon excitations.

It has been discussed previously that Monte Carlo simulation of the complete electron transport (including both elastic and inelastic processes) is possible only in the case of the local description of the electron-energy-loss process. The accurate consideration of the significant effect of the elastic scattering on the electron transport is also possible in this case, which is the main advantage of the application of Monte Carlo technique, beyond its promptness. On the other hand, the results plotted in Figs. 1 and 2 show that in the case of nonlocal description of the electron-energy-loss process the interference effects can cause a seemingly significant difference in the nature of the energy loss of the electron traveling in the near-surface region, even in the case of using realistic trajectories. Furthermore, the calculation of the average energy loss of the electrons (as other transport quantities as well) is considerably time consuming in the case of using realistic electron trajectories and the nonlocal description of the energy loss process. This is attributable to the fact that to calculate the actual value of the average energy loss of the traveling electron at the given point of the given trajectory requires the knowledge of the evolution of the electric fields induced in the sample by the electron at the earlier stage of its trajectory. The required time of this calculation is higher (with several orders of magnitude in a normal PC, i.e., it is several day for a given electron energy and geometry) in the case of real trajectories compared to the local description where the past history is ignored (and where the required time of calculation is only a few minutes). From these facts it is clear that the knowledge of the error caused by neglecting interference effects is essential in the case of the local description of the electron-transport process (applying Monte Carlo simulation). This missing information has a fundamental significance regarding the applicability of the Monte Carlo technique for modeling the entire transport of low-energy electrons in solids.

It has been shown and discussed above that the interference affects significantly only to the energy loss caused by surface plasmon excitations in the case of real trajectories. The same statement was made by Pauly and co-workers[25] who investigated this interference effect only in the case of V-shape trajectory approximation. To estimate the average error caused by the neglecting interference effect in the case of realistic electron trajectories and local description of the energy loss process, the probability density functions of the average electron energy loss in surface plasmon excitations were derived from the results gained by applying local as well as nonlocal approaches to the energy loss process of the backscattered electrons (i.e., the distributions of the dots projected to the y axis in Figs. 1 and 2). These distributions are plotted in Fig. 4 at $\alpha=0°$ and 85°. The difference, observable between the distributions derived by local and nonlocal approaches, disappears when the angle between the incoming and outgoing beam is increasing which is attributable to the less overlap of the incoming and outgoing parts of the electron trajectories. In connection with the distributions shown in Fig. 4 it should be noted that the distributions of the average energy lost by the electrons in surface plasmon excitations, calculated by means of integrating the surface stopping power along the individual electron trajectories, are plotted in Fig. 4 unlike the energy loss distributions of the electrons. Due to this fact, the positions of these distributions are related rather to the surface plasmon excitation probability than the energy position of the surface plasmon loss peak in the measured energy loss spectra. Furthermore, continuous energy loss is assumed when the average energy loss of the projectile is calculated by the integration of the stopping power along its trajectory instead of the "free flights between successive (elastic or inelastic) events" approximations. Therefore, the value of the calculated average energy loss along an individual electron trajectory can be an arbitrary positive real number in the first case (depending on the path length traveled by the electron).

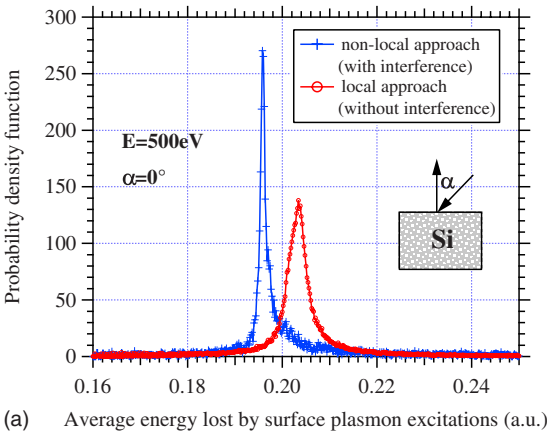

FIG. 4. (Color online) (a) Probability density functions of the average energy lost by electrons with a primary energy of 500 eV through surface plasmon excitations when backscattering from a Si surface, obtained by using local and nonlocal approaches to the electron-energy-loss process and applying realistic electron trajectories (derived by Monte Carlo simulation). The electrons were detected in the direction of the surface normal and the angle of the incoming electron beam was 0° with respect to the surface normal. (b) Same as in Fig. 4(a) in the case of the angle of 85° of the incoming electron beam with respect to the surface normal.

The distributions, derived by applying stochastic and deterministic approximations to describe the average energy loss of the backscattered electrons caused by surface plasmon excitations, become identical at high values of α (see Fig. 4). The expected values of the probability density functions of the average electron energy loss in surface plasmon excitations were calculated in the case of both local and nonlocal approaches to the electron-energy-loss process. The difference between these expected values are plotted in Fig. 5 as a function of the angle between the incoming and outgoing (normal emission) directions of the electrons (α). Figure 5 shows that the difference between the average value of the average energy lost by the electrons in surface plasmon excitations calculated by local and nonlocal approaches is about 6.2% for real trajectories even in the case of normal incidence and emission, where the influence of the interference effect (as predicted by the straight line or V-shape trajectory approximation) is the highest. As a consequence, the maximum value of the average error caused by the neglected

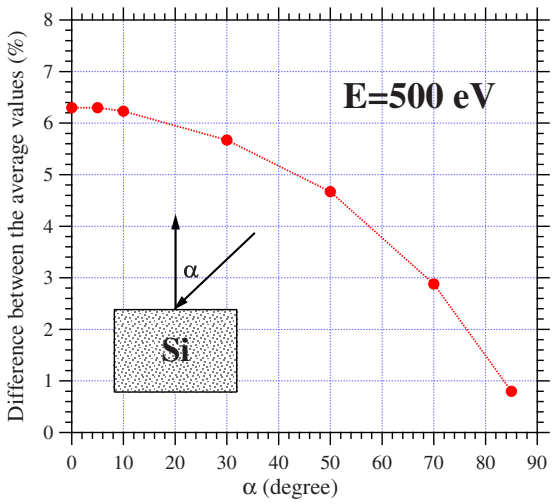

FIG. 5. (Color online) The relative difference of the average surface energy loss calculations applying local and nonlocal descriptions of the electron energy loss as a function of the angle of the incoming electron beam with respect to the surface normal.

interference effect is less than 6.2% when applying stochastic approach for describing the electron-energy-loss process in the case of realistic electron trajectories and electron energies not higher than 500 eV.

Furthermore, the error caused by neglecting interference effects is much smaller than the accuracy gained by fully considering the effects of elastic electron scattering as it has been pointed out by the present author recently.[26,27] It confirms the statements made above and all these facts make it clear why experimental evidence of the interference effect is missing. The experimental evidence for this interference effect might be provided using a near 180° scattering angle and lower electron energy, however, the experimental realization of this geometrical configuration as well as the accurate modeling of low-energy electron trajectories and the near-surface electron-transport processes is a challenge

IV. CONCLUSIONS

The local and nonlocal descriptions of the electron energy loss—caused by surface and bulk plasmon excitations—have been investigated and compared in detail. The average energy loss of the electrons with primary energy of 500 eV, backscattered from a Si sample have been calculated for both simple V shape and realistic electron trajectories derived by Monte Carlo simulation applying local as well as nonlocal descriptions based on the theory developed by Vicanek.[10] It has been pointed out that the oscillation feature appearing in the average energy lost by the backscattered electrons as a function of the maximum depth reached by them (as a consequence of the consideration of the interference effect in the case of nonlocal description of the electron-energy-loss process) is less pronounced than predicted by the simply V-shape trajectory approximation. It is attributable to the smaller overlap of the incoming and outgoing parts of the trajectories in the case of realistic electron trajectories due to the effect of elastic electron scattering. Furthermore, it has

been clearly shown that the interference has a significant effect only on the average energy lost by the electron through surface plasmon excitations. The probability density functions of the average energy lost by the electrons in surface plasmon excitations have been derived from the results calculated by using local and nonlocal descriptions of the energy loss process in the case of realistic electron trajectories. It has been pointed out through the comparison of these probability density functions that the results of these fundamentally different theoretical approaches of the energy loss process become the same when the incoming and outgoing parts of the electron trajectories are less overlapping. In addition, the average values of these probability density functions have been investigated as a function of the angle between the incoming and outgoing electron trajectories in order to give a quantitative estimate of the error caused by the neglected interference effect in the case of applying local description of the electron-energy-loss process. It has been shown that the value of this error is less than 6.2% when the electron energy is higher than 500 eV and the magnitude of this error caused by the neglected interference effect decreases by increasing the angle between the incoming and outgoing electron beams. It should be noted that earlier Pauly[25] and co-workers predicted a larger effect of the interference in the case of materials showing a sharp plasma resonance such as Si, while this effect was predicted to be smaller in the case of materials with a broader plasma resonance. Due to this fact the error caused by the neglected interference effect in the case of local description of the electron-energy-loss process predicted here is an upper limit in most cases of materials. As a consequence, fast modeling of the complete near-surface electron-transport process (including inelastic and elastic electron scattering) using Monte Carlo simulation techniques based on local description of the electron-energy-loss process is possible at these primary electron energies without significant errors due to the neglect of the interference effects.

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