Secondary-electron emission by 0.5-MeV/u H, He, and Li ions specularly reflected from a SnTe(001) surface: Possibility of the surface track potential reducing the secondary-electron yield at a semiconductor surface

Kenji Kimura,* Satoshi Usui, and Kaoru Nakajima

Department of Engineering Physics and Mechanics, Kyoto University, Kyoto 606-8501, Japan

We have measured secondary-electron (SE) yield γ induced by 0.5 MeV/u H, He, and Li ions specularly reflected from a SnTe(001) surface. The position-dependent SE production rate is derived from the observed γ. The SE production rate normalized by the observed mean square charge of the reflected ions is almost independent of the atomic number of the projectile ion. This indicates that the surface track potential induced by the projectile ion is negligibly small to affect the SE emission at semiconductor surfaces probably due to rapid relaxation processes.

PACS number(s): 34.50.Dy, 79.20.Rf

I. INTRODUCTION

Secondary-electron (SE) emission is one of the most fundamental phenomena in ion-solid interactions. There are two different mechanisms of the SE emission, i.e., potential electron emission (PEE), and kinetic electron emission (KEE) [1]. For the ion velocities larger than 10^7 cm/s, KEE is the dominant process over PEE except for highly charged ions. In this velocity region, the SE yield γ is often discussed in terms of the electronic stopping power S_e [2]

$$\gamma = \Lambda S_e . \qquad (1.1)$$

Simple theories predicted that Λ is independent of either the projectile atomic number Z_p or the projectile velocity [2]. In fact, for protons the proportionality between γ and S_e was experimentally confirmed in a wide energy range with somewhat varying material constants [2]. For heavy ions, however, it has generally been observed that Λ decreases with Z_p [3–5]. There are several models proposed to explain the observed Z_p dependence. However, the origin of the Z_p dependence is still unclear in spite of extensive studies.

The first attempt to explain the Z_p dependence of Λ was based on the fact that the effective charge in the preequilibrium region near the entrance surface is generally different from that in the equilibrium region [4,6]. In the heavy-ion measurements, the incident charge q_i is usually smaller than the mean equilibrium charge. Thus, the preequilibrium near surface stopping is smaller than the tabulated stopping. If the SE escape depth is comparable to or smaller than the charge-equilibration depth, use of the tabulated stopping power leads to the apparent reduction of Λ for heavy ions. Careful investigations with q_i close to the mean final charge have been performed to prevent the preequilibrium effects [7–9]. These results, however, showed strong Z_p dependence, indicating that the Z_p dependence cannot be explained by the preequilibrium effect only.

The second model is the recapturing of excited electrons by the ion track potential induced behind the projectile ion [7,10,11]. As the ion track potential increases with Z_p, the observed Z_p dependence can be explained. The ion track potential was indeed observed via energy shifts of Auger and convoy electrons emitted by the projectile ions interacting with insulator surfaces [12–14], whereas no energy shift was observed using carbon foils. Thus existence of the ion track potential in conducting materials is still under debate [7,9]. Nevertheless, a simple ion-track-potential model explained qualitatively the observed Z_p dependence [10,11].

The last model [7–9] relies on the fact that fast electrons emitted in the entrance surface region carry away a part of the deposited energy deep inside the solid. These fast electrons do not contribute to the electron emission but do contribute to the stopping power. If the fraction of the fast electron ejection increases with Z_p this results in a decrease of Λ. In fact, a reduction of low-energy electron emission (and so an increase of the fraction of fast electron emission) with increasing Z_p was found in a theoretical work on bare-ion hydrogen collisions [15]. This reduction comes mainly from close collisions. If close collisions are rejected in the SE measurement, the fraction of the fast electron emission does not depend on Z_p and the effect of the ion track potential can be clearly seen if it exists. This can be done by utilizing the so-called *specular reflection of fast ion*.

When a fast ion is incident onto an atomically flat single crystal surface at a glancing angle, the ion is reflected at the specular angle without penetration inside the solid [16]. This phenomenon called *specular reflection of a fast ion* is a kind of semiplanar channeling. The reflected ion experiences a number of correlated small-angle scatterings. There is no close collision. The SEs emitted by the specularly reflected ion are, therefore, mainly produced by distant collisions. In this situation, the last model does not work and this allows us to see the effect of the surface track potential on SE emission separately from the close-collision related effects. In the present paper, we measure the SE yield induced by 0.5 MeV/u H, He, and Li ions specularly reflected from a SnTe(001) surface, which is a typical narrow-gap semiconductor. The Z_p dependence of the SE yield is carefully ana-

*Author to whom correspondence should be addressed FAX: +81-75-753-5253. Email address: kimura@kues.kyoto-u.ac.jp

lyzed to see whether the surface track potential reduces the SE emission at a semiconductor surface or not.

II. EXPERIMENT

Details of the experimental procedure are described elsewhere [17]. A single crystal of KCl was cleaved in air and mounted on a high-precision five-axis goniometer in a ultrahigh-vacuum scattering chamber. A single crystal of SnTe(001) was prepared *in situ* by vacuum evaporation on the KCl surface at 250°C.

Beams of 0.5 MeV/u H^+, He^{2+}, and Li^{2+} ions from the 1.7-MeV Tandetron accelerator of Kyoto University were collimated by a series of apertures to less than 0.1 ×0.1 mm^2 and to a divergence angle less than 0.3 mrad. The beam was incident on the SnTe(001) at glancing angles θ_i = 1–7 mrad. The azimuth angle of the crystal was carefully chosen to avoid surface axial channeling.

The specularly reflected ions were selected by a small aperture (ϕ=1mm) placed 425 mm downstream from the target and the energy spectrum of the reflected ions was measured by either a magnetic spectrometer (for H and He ions) or a silicon surface barrier detector (for Li ions). The observed spectrum showed a multipeak structure. In the previous paper, we have shown that the dominant peak with the smallest energy loss (referred to as the first peak) corresponds to the specularly reflected ions and other small peaks correspond to subsurface channeled ions [16].

The charge-state distribution of the specularly reflected ions was also measured with the help of a magnetic charge-state analyzer. The measured charge-state distribution was almost independent of θ_i. The observed mean square charge $\langle q^2 \rangle$ for the specularly reflected ions was ∼1.0, 3.9, and 7.6 for 0.5 MeV/u H, He, and Li ions, respectively.

The SEs emitted by the reflected ions were measured by a microchannel plate (MCP) placed at ∼10mm in front of the SnTe(001) surface. The effective diameter of the MCP was 20 mm and the dimension of the crystal surface along the beam direction was 7 mm. The MCP was biased at +500 ∼+700V to collect all SEs emitted from the crystal surface. The MCP signals were measured in coincidence with the first peak ions (properly reflected ions) to reject the SEs emitted by the subsurface channeled ions as well as the background electrons [18].

The pulse height of the MCP signal is proportional to the number of the detected electrons [19]. The pulse height can be converted into the number of SEs by the usual way using the efficiency of MCP (ϵ=0.6 [20]) and the measured mean pulse height for single electron detection [17].

III. RESULTS AND DISCUSSION

Figure 1 shows the observed SE yield γ induced by 0.5 MeV/u H, He, and Li ions as a function of θ_i. The curves show the results of quadratic fitting to the data. The SE yield for Li ions decreases slightly with θ_i, while those for H and He are almost constant. The yield increases very rapidly with increasing Z_p, i.e., $\gamma \approx 33$, 180, and 370 for H, He, and Li ions, respectively, at θ_i=2mrad. Using the observed $\langle q^2 \rangle$
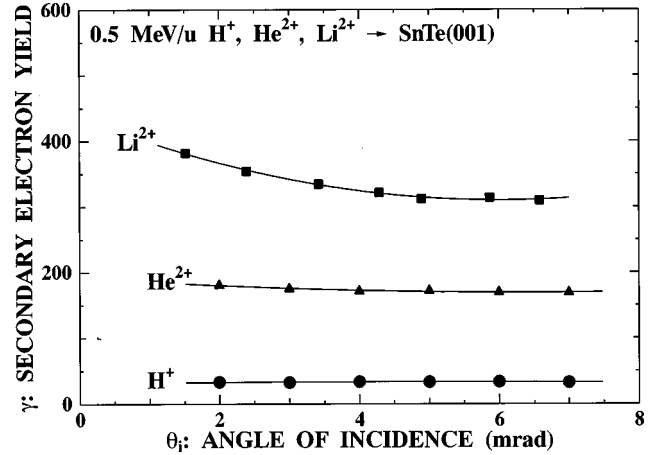

FIG. 1. Secondary-electron yields induced by 0.5 MeV/u H, He, and Li ions specularly reflected from a SnTe(001) surface as a function of the angle of incidence.

(1.0, 3.9, and 7.6 for H, He, and Li ions, respectively), the ratio $\gamma/\langle q^2 \rangle$ is calculated to be 33, 46, and 49 for H, He, and Li, respectively. As $\langle q^2 \rangle$ is a measure of the stopping power, this seems to contradict the generally observed result that $\Lambda = \gamma/S_e$ decreases with Z_p. A detailed analysis is required before concluding this anomalous Z_p dependence because the SE production rate $P(x)$ depends on the distance x from the atomic surface and the SE yield is obtained by integrating $P(x)$ along the ion trajectory. The trajectories of these ions are different from each other even at the same angle of incidence. We have to discuss Z_p dependence of $P(x)/\langle q^2 \rangle$ rather than that of $\gamma/\langle q^2 \rangle$.

From the observed $\gamma(\theta_i)$, the position-dependent SE production rate $P(x)$ can be derived [17]

$$P(x) = \frac{1}{2\pi E} \frac{dV(x)}{dx}\left[\gamma(0)\left(\frac{E}{V(x)}\right)^{1/2} \right.$$
$$\left. + \int_0^{\pi/2} \frac{d\gamma(\theta_i)}{d\theta_i}\bigg|_{\theta_i = \sqrt{\{V(x)/E\}}\sin(u)} du \right], \quad (3.1)$$

where $V(x)$ is the surface continuum potential and E the ion energy. We used the Molière potential for $V(x)$ and the result of the quadratic fitting for $\gamma(\theta_i)$. The obtained $P(x)$ normalized by $\langle q^2 \rangle$ is shown in Fig. 2. The normalized results converge to an almost universal curve within ±10%. This indicates that $P(x)/\langle q^2 \rangle$ is independent of Z_p although the normalized SE yield $\gamma/\langle q^2 \rangle$ increases rapidly with Z_p.

The different Z_p dependence between $\gamma/\langle q^2 \rangle$ and $P(x)/\langle q^2 \rangle$ can be explained by the following: the closest approach distance x_c to the surface is smaller for higher Z_p. Because $P(x)$ decreases almost exponentially with x (see Fig. 2), the smaller x_c results in a relatively large SE yield. Moreover, the trajectory length is longer for higher Z_p. Thus $\gamma/\langle q^2 \rangle$ increases with Z_p even if $P(x)/\langle q^2 \rangle$ is almost independent of Z_p.

The position-dependent stopping power $S(x)$ can also be derived from the observed energy loss of the reflected ions using a similar equation to Eq. (2) [replacing $P(x)$ and $\gamma(\theta_i)$
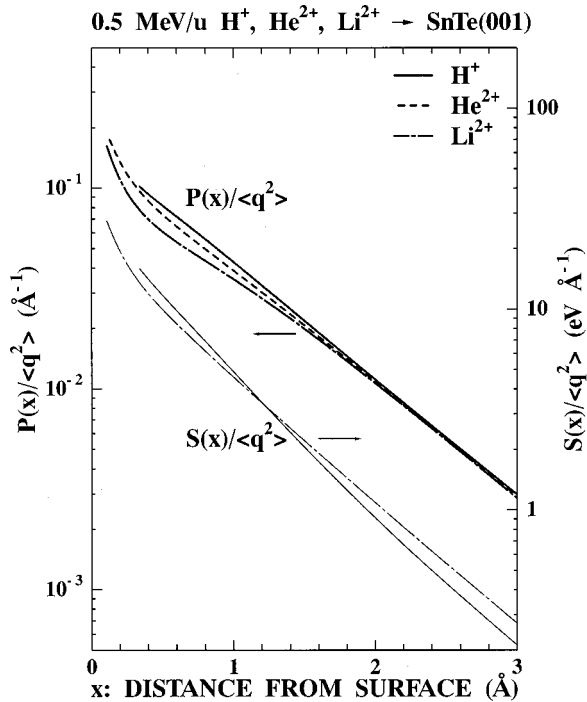
FIG. 2. Secondary-electron production rates for 0.5 MeV/u H, He, and Li ions at a SnTe(001) surface. The production rates normalized by the observed $\langle q^2 \rangle$ are shown. The observed position-dependent stopping power normalized by $\langle q^2 \rangle$ is also shown for H and Li ions.

with $S(x)$ and $\Delta E(\theta_i)$, respectively]. The obtained $S(x)$ normalized by $\langle q^2 \rangle$ for H and Li ions are also shown in Fig. 2. The normalized surface stopping powers agree with each other showing that $\langle q^2 \rangle$ is a good measure for the stopping power as was assumed above.

The present result indicates that the effect of the surface track potential on SE emission is negligibly small at the SnTe(001) surface. The surface stopping power for 0.5 MeV/u Li is as large as 100 eV/Å at $x \sim 0.4$ Å. According to the simple ion track model, the stopping power of 100 eV/Å is large enough to induce the strong ion track potential which reduces the SE yield considerably even for the foil transmission case [11]. In fact, from the obtained $P(x)$ it is estimated that two holes per surface atom are created by 0.5 MeV/u Li at $x \sim 0.4$ Å in the atoms located under the ion trajectory. These holes induce a large surface track potential. Nevertheless, we have observed no significant effect. This suggests that the surface track potential is rapidly relaxed at a semiconductor surface. The interaction time of the reflected ion with the surface is some femtoseconds in the present case (the length of the trajectory in the vicinity of the surface is several hundred atomic units and the ion velocity is 4.5 a.u.). This indicates that the relaxation time for the surface track potential at the SnTe(001) should be smaller than about a femtosecond.

IV. CONCLUSION

Position-dependent SE production rates are derived from the observed SE yields for 0.5 MeV/u H, He, Li ions on SnTe(001). The SE production rate normalized by $\langle q^2 \rangle$ is found to be almost independent of Z_p, indicating that the surface track potential hardly affects SE emission at the SnTe(001), although a large surface track potential is expected from the observed SE production rate for Li if the relaxation process is not taken into account. This suggests that the induced surface track potential is rapidly relaxed within $\sim$ fs at the semiconductor surface.

[1] See, for example, *Particle Induced Electron Emission II*, edited by G. Hohler and E. A. Niekisch, Springer Tracts in Modern Physics Vol. 123 (Springer, Heidelberg, 1992).

[2] D. Hasselkamp, in *Particle Induced Electron Emission II*, Ref. [1].

[3] A. Clouvas, H. Rothard, M. Burkhard, K. Kroneberger, C. Biedermann, J. Kemmler, K.O. Groeneveld, R. Kirsch, P. Misaelides, and A. Katsanos, Phys. Rev. B **39**, 6316 (1989).

[4] H. Rothard, K. Kroneberger, A. Clouvas, E. Veje, P. Lorenzen, N. Keller, J. Kemmler, W. Meckbach, and K.O. Groeneveld, Phys. Rev. A **41**, 2521 (1990).

[5] H. Rothard, K. -O. Groeneveld, and J. Kemmler, in *Particle Induced Electron Emission II*, Ref. [1].

[6] H. Rothard, J. Schou, and K.O. Groeneveld, Phys. Rev. A **45**, 1701 (1992).

[7] H. Rothard, J.-P. Grandin, B. Gervais, M. Caron, A. Billebaud, A. Clouvas, R. Wünsch, C. Thierfelder, and K.-O. Groeneveld, Nucl. Instrum. Methods Phys. Res. B **125**, 35 (1997).

[8] H. Rothard, M. Jung, M. Caron, J.-P. Grandin, B. Gervais, A. Billebaud, A. Clouvas, and R. Wünsch, Phys. Rev. A **57**, 3660 (1998).

[9] G. Schiwietz and G. Xiao, Nucl. Instrum. Methods Phys. Res. B **107**, 113 (1996).

[10] J.E. Borovsky and D.M. Suszcynsky, Phys. Rev. A **43**, 1433 (1991).

[11] O. Benka, A. Schinner, T. Fink, and M. Pfaffenlehner, Phys. Rev. A **52**, 3959 (1995).

[12] G. Schiwietz, P. Grande, B. Skogvall, J.P. Biersack, R. Köhrbrück, K. Sommer, A. Schmoldt, P. Goppelt, I. Kádár, S. Ricz, and U. Stettner, Phys. Rev. Lett. **69**, 628 (1992).

[13] G. Xiao, G. Schiwietz, P.L. Grande, N. Stolterfoht, A. Schmoldt, M. Grether, R. Köhrbrück, A. Spieler, and U. Stettner, Phys. Rev. Lett. **79**, 1821 (1997).

[14] G.R. Gómez, O. Grizzi, E.A. Sánchez, and V.H. Ponce, Phys. Rev. B **58**, 7403 (1998).

[15] P.L. Grande and G. Schiwietz, J. Phys. B **28**, 425 (1995).

[16] K. Kimura, M. Hasegawa, Y. Fujii, M. Suzuki, Y. Susuki, and M. Mannami, Nucl. Instrum. Methods Phys. Res. B **33**, 358 (1988).

[17] K. Kimura, S. Ooki, G. Andou, K. Nakajima, and M. Mannami, Phys. Rev. A **58**, 1282 (1998).

[18] K. Kimura, S. Ooki, G. Andou, and K. Nakajima, Phys. Rev. A **61**, 012901 (2000).

[19] B. Monart, Ph.D. thesis, Paris Sud University, 1988.

[20] M. Galanti, R. Gott, and J.F. Renaud, Rev. Sci. Instrum. **42**, 818 (1971).