Quasiresonant electron exchange in the emission of secondary ions from the surface of silicon

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Bombardment of the surface has revealed that the energy and angular distributions of excited secondary silicon ions are oscillating in nature. To account for this phenomenon, a quasiresonant electron-exchange mechanism is proposed.

In our experiments we used the coincidence method. We detected the positive secondary ions of the Si^+ target, which matched in terms of the production time the photons of a particular wavelength emitted from the sputtered excited Si^{+*} ions.

As a sample we used a silicon single crystal. In the measuring chamber the sample was thermally outgassed and simultaneously purified by an ion beam. During the measurements, the sample was heated to 250° C, causing the charge to be removed from the bombarding zone due to the increase in the intrinsic conductivity of silicon. The sample was bombarded normal to the surface by 7.5-keV Ne^+ ions. The current density of the beam was $j = 150\ \mu\text{Å}/\text{cm}^2$ and the pressure of the residual gasses was $p = 5\times 10^{-7}$ torr. The ion-photon emission lines were identified by means of an interference filter 382 ± 15 nm. The secondary Si^+ ions were detected by an energy analyzer with a resolution $E/\Delta E = 100$ in a plane without any low-index directions at a 30° angle with respect to the bombarded surface. The transmission band of the interference filter contains three additional lines: the Si^* line and two Si^{++*} lines. These lines, however, do not affect the distribution, since only the Si^+ ions are detected in coincidence. The time resolution of the coincidence circuit is $\tau = 50$ ns.

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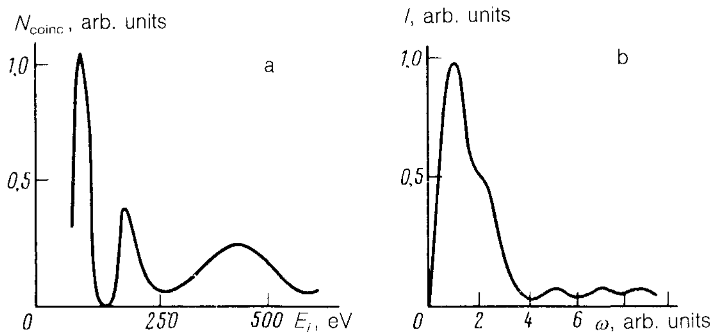

FIG. 1. (a) Number of coincidences of Si II photons with Si^+ ions as a function of the energy of Si^+. (a) and (b) The spectral-density function found in the spectral analysis of curve 1.

Figure 1a shows the number of coincidences, N_{coinc}, between the secondary Si^+ ions emitted from the (111) surface of Si as a result of ion bombardment and the photons with $\lambda = 385$ nm, as a function of the energy E of the secondary Si^+ ions, i.e., the energy distribution of the excited secondary Si^{+*} ions. Similar oscillations were observed in Ref. 1 in the scattering of He^+ ions by the surface of certain solids. They were explained in Ref. 1 by the nearly resonant vibrational electron exchange (charge exchange) between the energy level of the atomic shell of the solid and the ground state of the atomic particle which moves away from the surface in the case of a particular ratio between the duration of the transition and the duration of the interaction of the atom with the solid. The interaction time changes as a result of changing the particle velocity, which leads to a change in the phase of the electron exchange at the point the atomic particle emerges from the region of interaction with the solid. This process can take place when the resolved energy levels of the atoms of a solid differ from the energy level of the ground state of an atom by no more than $\Delta E = 10$ eV. According to Ref. 2, in the case of a quasiresonant electron exchange of this sort, the probability that an ion will retain all of its charge state after interacting with the surface of a solid is given by the expression $P = A + B\cos^2\delta/2$, where A and B are coefficients which are nearly independent of the collision energy, and the δ phase is given by

$$\delta = \frac{1}{\hbar}\int \Delta E dt \cong \frac{2}{\hbar v}\int_{R_0}^{R_m} \Delta E(R) dR = \frac{2}{\hbar v}\langle \Delta E \Delta R \rangle .$$

In this expression the approximate equality is written under the assumption that the relative velocity of the interacting particles is constant, ΔE is the difference in energies of the levels between which there is an electron exchange, and R_m and R_0 are the minimum and maximum distances at which the atomic particles interact. From the expression for δ we see that with the variation of $1/v$, the probability P changes in accordance with the harmonic law at a frequency which is determined by $\langle \Delta E \Delta R \rangle$ ($\Delta E \Delta R$ changes only very slightly in this case).

The use of this approach in our case suggests that we are dealing with a quasiresonant process. By carrying out a spectral analysis of the curve in Fig. 1a, after replotting it as a function of $1/\sqrt{E} \sim 1/v$, we will obtain a characteristic frequency of the spectral density function (Fig. 1b). Estimates put the value of $\langle \Delta E \Delta R \rangle$ at ~ 0.3 Å·eV, which is well below a similar value encountered in the process analyzed in Ref. 2. Consequently, the electron exchange in our case should occur between more closely spaced levels, as will be shown below.

The dominance of a certain frequency of the spectral density function is evidence that there is a dominant mechanism responsible for the charge exchange. Analysis of the electronic structure of silicon (Fig. 2) shows that near the free level of Si^{++} ion ($E = 5.3$ eV), there is a band of surface and impurity levels of Si, $E = 6.0$–5.0 eV (Ref. 3), which can participate in the electron exchange ($\Delta E < 1$ eV).

We are accordingly suggesting the following mechanism to explain the curve in Fig. 1a. The bombardment of silicon by Ne^+ ions accelerated as a result of "hard" Ne–Si or Si–Si collisions causes the formation of a vacancy in the deep L shell. The Auger effect involving the outer M shells (the LMM transition) accounts for the formation of a doubly charged Si^{++} ion (analysis of the energy spectrum of secondary electrons shows that there is a maximum at $E_e = 86$ eV, which corresponds to the Auger electrons emitted as a result of the LMM transition). Charge exchange to an excited Si^{++} level as a result of an electron exchange with the surface silicon levels (Fig. 2) gives rise to oscillations in the yield of Si^{+*} as a function of the time of interaction of the particle with the surface, i.e., as a function of the perpendicular component of its velocity, $v_\perp$. At a particular energy, the maximum production of Si^{+*} corresponds to the maximum number of coincidences of Si^+ ions and photons which are produced as a result of the decay of this excited state.

Since the dominant feature in a resonant process of this sort is the time of interaction of the particle with the surface, which is determined by $v_\perp$, a change in the viewing angle at a specified viewing energy also should lead to an oscillating form of

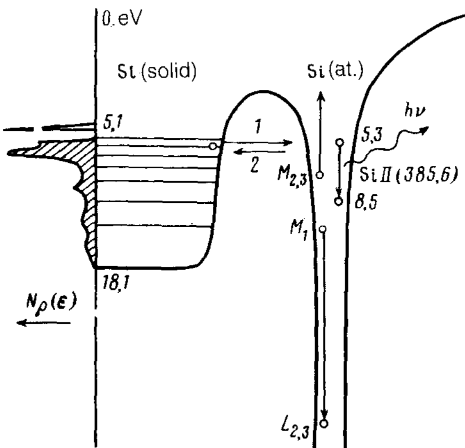

FIG. 2. Electron energy diagram illustrating resonant tunneling due to radiative neutralization (transition 1) and radiative ionization (transition 2).

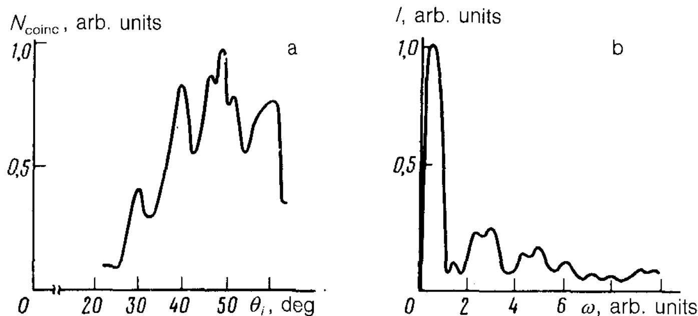

FIG. 3. (a) Number of coincidences of Si II photons with Si^+ ions as a function of the viewing angle of Si^+ ions. (a) and (b) The spectral-density function found in the spectral analysis of curve 3.

the angular dependence of the coincidences, and this was indeed observed by us experimentally (Fig. 3). Estimates with allowance for resonant electron tunneling time and for secondary-ion velocities characteristic for our experiment show that an electron exchange can occur even at a range shorter than 5 Å from the surface, consistent with the data of Ref. 4. According to Ref. 4, such an exchange can occur at distances up to 10 Å from the surface.

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[1]R. L. Erickson and D. P. Smith, Phys. Rev. Lett. **34**, 297 (1975).
[2]J. C. Tully, Phys. Rev. B **16**, 4324 (1977).
[3]S. Ciraci, B. Butz, E. M. Oellig, and H. Wagner, Phys. Rev. B **30**, 711 (1984).
[4]H. D. Hagstrum, Phys. Rev. **123**, 758 (1961).

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