

# Two-peak energy distributions of secondary ions sputtered from the surface of an aluminum single crystal

A. A. Kosyachkov

*Institute of Metal Physics, Academy of Sciences of the Ukraine, 252142 Kiev, The Ukraine*

(Submitted 23 April 1993; resubmitted 29 June 1993)

*Pis'ma Zh. Eksp. Teor. Fiz.* **58**, No. 3, 202–204 (10 August 1993)

Two-peak energy distributions have been observed for the secondary-emission ions from the surface of an Al(001) single crystal. The mechanism shaping these distributions is discussed. A focusing of the energy of a cascade of atomic collisions in an ordered crystal lattice is taken into account. The point defects caused in the surface by ion bombardment are also taken into account.

Research on the energy distributions and angular distributions of atomic particles emitted by solid surfaces during ion bombardment leads to a better understanding of the physics of sputtering and secondary ion emission. This research also promotes the development of technological and diagnostic applications of these emission processes. For example, it was recently established<sup>1,2</sup> that various binding states of atoms of a heterogeneous surface are imaged as distinct peaks in corresponding energy spectra of secondary ion emission.

The results of the study which we are reporting here show that another fundamental characteristic of a surface—its atomic structure—may also be manifested in the formation of an additional peak in the energy distributions of secondary ions. The situation is illustrated by Fig. 1, which shows energy distributions of secondary Al<sup>+</sup> ions emitted along the normal to the surface of an alloy, the surface of a polycrystalline sample, and the (001) face of an aluminum single crystal. In each case the surface was bombarded by 6-keV argon atoms at an angle of 60°. It can be seen from Fig. 1 that the ordered arrangement of atoms in the single crystal gives rise to an additional high-energy peak in the secondary ion emission. It has been established that this peak disappears after prolonged bombardment of the surface by argon ions or after texturing of the single crystal by rolling. The mechanism for the formation of the fine structure in the energy spectra of the secondary ion emission involved here is thus specific to a single crystal.

A focusing of the energy of a cascade of atomic collisions in high-quality crystals, manifested in the formation of an additional high-energy peak in the time-of-flight spectra of neutral atoms, was studied previously<sup>3</sup> on the (001) and (011) faces of a gold single crystal. The high-energy peak corresponds to gold atoms focused in a [001] low-index direction as these atoms move through the ring of atoms of the second surface layer, which acts as a dispersive lens, as illustrated in the inset in Fig. 2. According to calculations based on the equations proposed in Ref. 3, the contribution of the high-energy peak of secondary aluminum ions observed in the present experiments [these ions are sputtered in the (001) direction; the polar angle of the emission

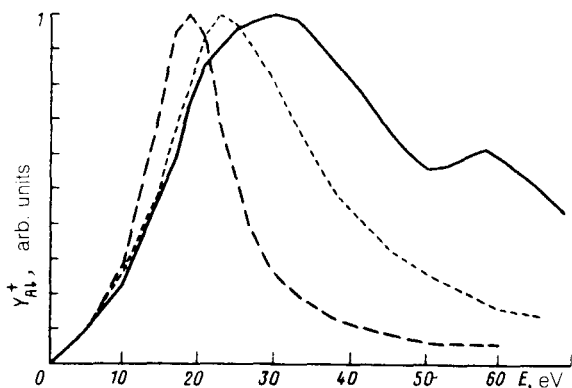


FIG. 1. Energy distributions of secondary aluminum ions emitted from the surfaces of various samples. 1—Polycrystalline alloy Al-15%Cu; 2—polycrystalline Al; 3—Al(001) single crystal.

is  $\theta=0^\circ$ ] can indeed be described well on the basis of this focusing model if we use 72 eV as the critical energy for focusing by an atomic ring and if we use the binding energies recommended in the literature for the aluminum atoms which make up the first surface layer [3.80 eV (Ref. 4)] and the second layer [3.39 eV (Ref. 4)], and if we use 0.4 (Ref. 3) as the mean square displacement of the atoms due to vibrations.

As can be seen from Fig. 2, however, the two-peak structure is seen in the energy distributions of the secondary aluminum ions not only in the [001] focusing direction but also at other emission polar angles. This result can be explained on the basis of a deviation from the conditions for ideal focusing due to the formation of vacancies in the first surface layer, which is subjected to ion bombardment in the course of the study. An isolated vacancy, e.g., as shown by the open circle in the inset in Fig. 2, belongs to four focusing rings of the first layer; it is also a nearest neighbor of atoms of five rings of the second layer (one of these rings is shown in the inset). This vacancy disrupts the symmetry of the rings of the first layer and the ideal focusing by four of the five rings of the second layer, since the smallest distance between atoms of a ring is the same as the distance between the vacancy and the nearest atoms of the rings of the second layer ( $d/\sqrt{2}$ , where  $d$  is the lattice constant). The presence of this vacancy thus leads to a nonzero impact parameter as the focused energy acts on an atom of the first layer above the ring. This vacancy simultaneously makes possible a sputtering of this atom at a nonzero angle  $\theta$ . In an ideal lattice, this possibility is forbidden by the symmetry of the rings of the first layer.

It should be noted, however, that the proposed interpretation is valid for the sputtering of not only secondary ions but also neutral atoms. This interpretation thus requires an experimental test through energy- and angle-resolved detection of neutral particles. In particular, it has been established<sup>5</sup> that the energy distributions of secondary rhodium ions emitted from the (111) face of a rhodium single crystal have an additional high-energy peak—one which is not observed in the energy spectra of the sputtering of neutral rhodium atoms. Malafsky and Winograd<sup>5</sup> believe that certain

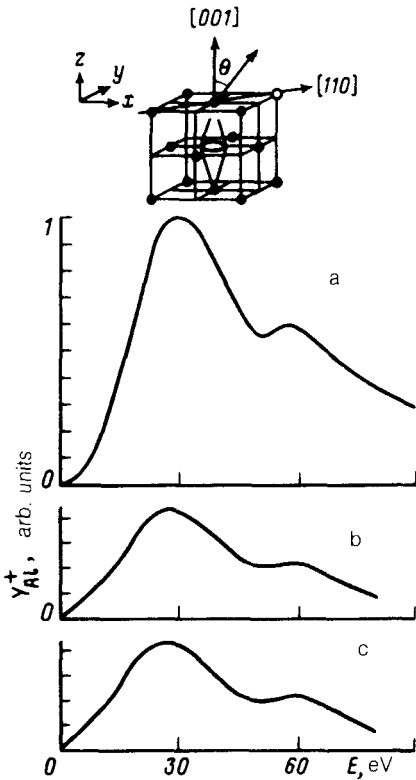


FIG. 2. Energy distributions of the second aluminum ions emitted from Al(001) surfaces at various polar angles  $\theta$ : a— $0^\circ$ ; b— $20^\circ$ ; c— $36^\circ$ .

atomic collisions—collisions which are rather rare but which involve very large amounts of energy—can distort the electronic structure of the crystal to the point that excited states of sputtered atoms decay in vacuum, giving rise to secondary ions with the energy which is characteristic of the high-energy peak. The contribution of such secondary ions to the energy spectrum of secondary ion emission is small, but it may nevertheless be noticeable if the overall probability for ionization of the sputtered atoms by the usual mechanisms<sup>6</sup> is not large.

The use of the latter explanation for the results of the present study is slightly problematical, since the secondary ion emission of aluminum, in contrast with that of rhodium, is characterized by one of the highest ionization probabilities among metals.<sup>6</sup> Nevertheless, definitive conclusions regarding the mechanism for the formation of the two-peak energy distributions of secondary ion emission of an aluminum single crystal can be reached only through a comparison of the sputtering spectra of neutral and ionized particles. Reaching definitive conclusions will also require a detailed study of the dependence of the observed effect on the bombardment dose and a simulation of the scattering of surface atoms by molecular-dynamics methods incorporating collective interactions of atoms.

<sup>1</sup> A. A. Kosyachkov, V. T. Cherepin, and S. M. Chichkan', JETP Lett. **47**, 181 (1988).

- <sup>2</sup>A. A. Kosyachkov, V. T. Cherepin, S. M. Chichkan', and A. G. Klimenko, *Sverkhprovodimost'* (KIAE) **3**(8), 1664 (1990) [*Superconductivity* **3**(8), 1339 (1990)].
- <sup>3</sup>S. Ahmad and M. W. Thompson, *Philos. Mag.* **A50**, 299 (1984).
- <sup>4</sup>P. Siegmund, *Sputtering of Solids by Ion Bombardment* [Russian translation] (Mir, Moscow, 1984).
- <sup>5</sup>G. P. Malafsky and N. Winograd, *Surf. Sci.* **257**, 41 (1991).
- <sup>6</sup>V. T. Cherepin and M. A. Vasil'ev, *Secondary Ion-Ion Emission of Metals and Alloys* (Naukova Dumka, Kiev, 1975).

Translated by D. Parsons