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OBSERVATION OF A NEW ATOMIC-LIKE PEAK IN THE ION-INDUCED AUGER SPECTRUM OF Si

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We have observed Si L-shell Auger electrons from a silicon surface bombarded with 20 keV Ar⁺ ions at different angles of incidence. The measurements of angle-resolved electron energy distributions allowed us to separate the contributions to the Auger electron spectra coming from de-excitations inside and outside the solid. At grazing angles of incidence and observation, the Auger electron distributions resemble those from gas-phase atomic collisions. In these conditions we observed an atomic-like Auger peak with an energy close to that of the high energy edge of the Si L2,3VV transition.

The L-Auger spectra of Mg, Al, and Si excited by heavy-ion bombardment have some interesting features which are the subject of current studies. Three or more narrow peaks are clearly observed superimposed on a broad structure. The narrow peaks, resembling atomic-like transitions, have received different interpretations [1-4]; the main point of discussion being whether these Auger electrons are emitted inside or outside the solid [1,5-7]. The broad structure is very similar to the Auger spectrum excited by electron bombardment, and has been unanimously assigned to L2,3VV transitions [1-4] involving two valence band (V) electrons. A close comparison reveals that in the ion-impact case the broad structure extends to higher energies than in electron-induced spectra. Some authors observed this discrepancy in the high energy edge in Al and Si and ascribed it to possible changes in the electron energy distribution in the solid during ion bombardment of Al[3], and charging of the sample in the case of Si[2].

Recently, Whaley and Thomas [8] (WT) confirmed the existence of this discrepancy in the Al and Si spectra, and its absence in the Mg spectrum.

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These authors also proposed a detailed modelling of the spectra which accounts for all the significant features. Their model assumes that each spectrum is the superposition of a band-like component, taken equal to the electron-induced L$_{2,3}$VV spectrum, and atomic-like peaks corresponding to excited sputtered neutral atoms and ions decaying in free space. To obtain an accurate fit of the Al and Si spectra the authors assumed the existence of a new atomic-like peak, located at almost the same energy as the high-energy edge of the L$_{2,3}$VV feature. Since this peak is superimposed on the sharp edge of the L$_{2,3}$VV feature, it appears in normal spectra only as a small shoulder, and could account for the mentioned shift of the high-energy edge in the ion-induced spectra.

Saiki and Tanaka [6] (ST) showed that when Auger electron spectra are observed at emission angles close to the surface, the atomic-like peaks predominate over the broad band-like component. They found also a good agreement with the assumption of a cosine distribution for the bulk structure and an isotropic distribution for the atomic-like peaks, coming from the decay of excited sputtered atoms in vacuum. In contradistinction with WT they attributed the small shoulder in the high-energy edge to Auger electrons generated inside the solid.

Our work is intended to clarify this controversy. We studied the Auger electron spectra of Si bombarded with 20 keV Ar$^+$ ions at different angles of incidence of the projectile and varying the emission angle at which the electrons are observed.

Experiments were performed under ultra-high vacuum conditions (< 10$^{-9}$ Torr) with an equipment which will be described in detail elsewhere.

The sample was a commercial single crystal Si (1000 Ω cm), 4 mm wide, mirror polished. Ar$^+$ ions were produced in a radio frequency source and mass analyzed by a switching magnet. The beam was 0.5 mm in diameter and its angular dispersion was 0.1°. Electrons were energy analyzed with a cylindrical mirror analyzer (CMA) designed for angular measurements, particularly near the incident beam direction. The energy resolution was 1.5%. Fig. 1 shows the experimental arrangement. The ion beam forms an angle of 42.3° with respect to the spectrometer axis and the angle between this axis and the acceptance cone of the analyzer is also 42.3°. The analyzer could be rotated 180° around its symmetry axis, under this condition the axis of the acceptance cone describes a cone with a semi-aperture of 42.3°. This disposition allows the observation angle to be varied from 0° to 84.6° with respect to the incident beam direction. The angular acceptance is 3.2°.

The sample could be rotated around the analyzer axis changing the beam incidence angle from 90° to 47.7° with respect to the sample normal.

Fig. 2a shows the Si Auger spectrum taken at a projectile incidence angle of 47.7° and an electron emission angle of 55°; the angles are measured with respect to the sample normal. This spectrum is quite similar to spectra already
published [1,6,8]. Three atomic-like peaks, A, B and D, are clearly observed superimposed on the broad structure associated with \( \text{L}_{2,3}\text{VV} \) transitions. Two small shoulders, C and E, are detected on the high and low energy edge of the main atomic-like peak, respectively. The structure F at 108.8 eV is normally assigned to Auger transitions in Si atoms with a double \( \text{L}_{2,3} \) vacancy.

We have searched for the existence of an atomic-like peak in the region of the shoulder E, by measuring Auger spectra at an incidence angle of 47.7\(^\circ\) and varying the observed electron ejection angle in the angular region 47\(^\circ\)–90\(^\circ\).

Figs. 2a and 2b show two limiting cases of Si Auger spectra taken under different emission angles, 55\(^\circ\) and 86\(^\circ\) respectively.

We can observe in these figures a strong variation of the relative intensities of band-like and atomic-like components, but the absolute intensities of peaks B and D and their width at half maximum (FWHM \( \approx \) 4.4 eV) remain independent of the emission angle (within experimental error) in full agreement with ST.

The band-like contribution decreases with increasing emission angles due to the small attenuation lengths of Auger electrons in solids. Electrons which escape from the solid at angles close to the surface should suffer, on the average, more inelastic collisions than those which escape near the surface normal. Additionally they are reflected at the surface when their velocity in the direction of the surface normal is not enough to traverse the surface barrier.
The isotropic behaviour of the narrow peaks confirms previous assumptions that they correspond to Auger electrons emitted in the vacuum by the sputtered target atoms [2–4,6–8]. We can also see in fig. 2b that feature E becomes clearer than in the previous spectrum, thus behaving like an atomic-like peak, in contrast with the behaviour of the broad structure.

With this encouraging result we measured similar spectra but bombarding the sample at grazing incidence. In this condition, the atomic collision cascade produced by the projectile should develop closer to the surface. Thus we expect that the atomic-like peaks will predominate even more over the band-like component.

Fig. 3 shows the Si Auger spectrum taken with a projectile incidence angle of 86° and an electron emission angle of 78° (16° with respect to the incident
beam direction). In this condition of almost grazing observation the apparent size of the beam spot is 1.5 mm, which does not change the analyzer performance. It is observed that the broad feature has almost disappeared, though not completely, while features C and E appear as well-defined atomic-like peaks. We can also notice that atomic-like peaks became narrower than in previous spectra (FWHM 2.7 eV).

At grazing incidence almost all the projectiles are reflected at the surface [9], diminishing the total Auger electron yield. In the ideal conditions of atomically flat surfaces all the projectiles are reflected, and excitation collisions, which according to the electron promotion model require small distances of closest approach, are not possible. The ejection of sputtered recoils, excited in a projectile–target collision, may be possible due to the presence of atomic steps in the surface. To excite a Si 2p electron, the distance of closest approach must be less than 0.65 Å and the corresponding most probable scattering angle of
the recoils [10] is less than $13^\circ$ with respect to the surface normal. Therefore
the Doppler broadening [3] for observation angles close to the surface should
be small, as observed.

Finally we must point out that peak A has a behaviour different from that
of the other atomic-like peaks, it is broader than B, C, D and shifts to lower
energies when the emission angle is close to the surface (see figs. 2b and 3). We
have no explanation for this effect.

In conclusion, using angle-resolved electron energy distribution measure-
ments combined with bombarding the sample at grazing incidence, we observed
Auger spectra of Si which resemble those from gas-phase atomic collisions and
present conclusive evidence of the existence of an atomic-like peak as post-
tulated by WT with almost the same energy as the high energy edge of the
$L_{2,3}VV$ transition.

References