STS Study of Spectrum of Surface Electronic States in Bismuth.

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Abstract

Low temperature scanning tunneling spectroscopy of trigonal (0001) plane and "quasitrigonal" plane of twin interlayer on a cleaved bismuth surface is performed. It is found that both crystallographic planes are characterized by surface electron states with spectra exhibiting clearly defined singularities in the energy range ∓ 1 eV. An analysis of the tunneling spectra has revealed the existence of a two-dimensional surface layer with a typical of metals density of electronic states.

Key words: STM/STS ; surface ; metals ; electronic states

Considerable interest in electronic properties of bismuth surface results from very unusual electronic properties of bulk bismuth. It is known to be a semimetal, the concentration of conduction electrons in bismuth is by five orders of magnitude smaller than in normal metals, their wavelength and Debye screening radius are much longer than the interatomic distance, so the electronic spectrum near Bi surface cannot remain unchanged while electrons interact with surface, and it is quite probably that the properties of electrons in a two-dimentional layer near the surface differs from the properties of bulk electrons. From this point STM/STS study of bismuth surface seems to be especially interesting.

We performed the simultaneous spectroscopy of two different crystal planes, namely, a trigonal (0001) (perpendicular to the Γ-T direction) and a twin interlayer surface (perpendicular to one of three equivalent Γ-L directions)[1]. The comparison of tunneling spectra for different planes made it possible to relate the singularities of the density of state to surface, rather than to bulk, states. This is a direct proof of the existence of surface states.

The investigations were performed in a low-temperature setup [2] using a scanning tunneling microscope [3]. The details of experimental technique can be found in [1].

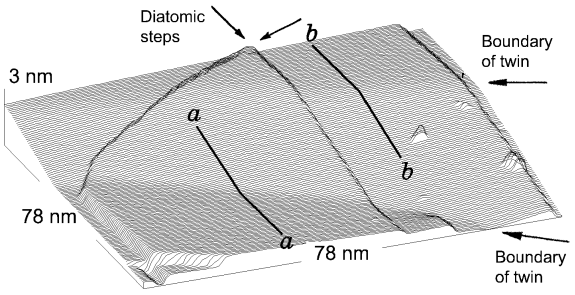

Fig. 1. An STM image of a region of a cleaved bismuth surface with a twin interlayer; *(a-a)* and *(b-b)* - lines along which sets of current-voltage characteristics were registered. One can see terraces of diatomic height and (in the lower right-hand corner)point defects.

The image of a surface with twin interlayer is shown in Fig.1. Its appearance is quite classical: the horizontal region (trigonal plane) changes to the inclined one (twin interlayer surface), and then to horizontal (trigonal plane) again, at a different level. The angle between the planes differs from 180° by $\pm 2.4^\circ$ in accordance with known Bi lattice.

Arrays of current-voltage characteristics (CVC) were registred during the moving of the STM tip by the 1.5 nm steps along the *(a-a)* and *(b-b)* lines plotted in

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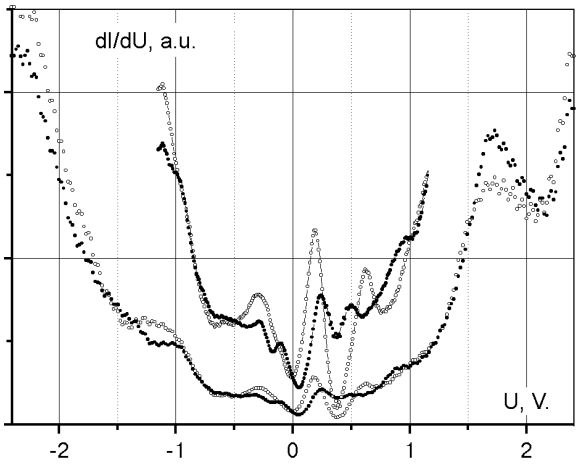

Fig. 2. Differential CVCs obtained by numerical differentiation with smoothing of measured CVCs. Dots indicate the trigonal planes, hollow dots indicate the quasitrigonal plane.

Fig.1. From these arrays we can extract CVCs or differential CVCs at various tip positions (Fig.2) or current versus coordinate dependencies at selected voltages (Fig.3). One can see from Fig.3, that outside the regions of about 4÷6 nm at the twin boundary, the current at each voltage remain constant within the corresponding trigonal or quasitrigonal region. The same is true for the CVCs - they coincided with one another for all places on the trigonal planes as well as on the quasitrigonal plane.

The typical for the trigonal plane and for the quasitrigonal plane (when far enough from the twin boundary) differential CVCs are given in Fig.2. One can see that they differ considerably for crystallographically different planes, especially, in the voltage range from -0.5 to +1 V. This fact allows one to state with assurance that no singularities due to the electron spectrum of the tip are observed on tunneling spectra, because, with the tip being the same, the singularities on the differential CVCs for the trigonal and quasitrigonal planes are completely different: the minima and maxima either do not coincide as regards their positions, or they differ in relative magnitude.

As it is seen in Fig.2, the current derivatives increase rapidly at high voltages. But this increase is associated primarily with the variation in the transparency of the tunneling barrier. It is easy to estimate that, at U = ±2V, an increase in the transparency of the tunneling barrier leads to a current increase by a factor of 10 to 15. If this is taken into account, one can conclude from Fig.2 that the density of states in the entire investigated voltage region, even at U = 0, has nearly the same magnitude, which must be of the order of 0.1÷1 electron/atom×eV. This situation is dramatically different from the situation for the bulk electrons in Bi, which have abnormally small density of states

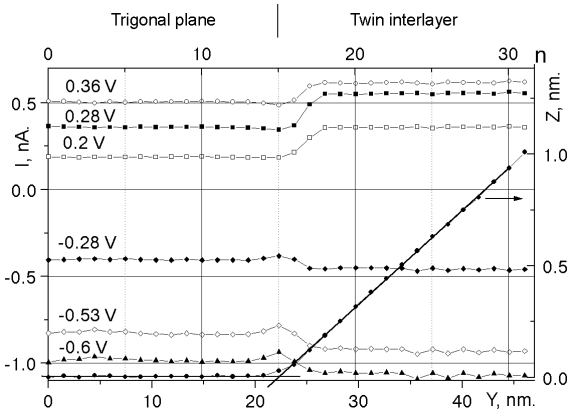

Fig. 3. The tip position z and the tunneling current as functions of the coordinate y along the surface for different values of voltage.

(of the order of 10^{-3} electron/atom×eV) in the vicinity of some hundredth electron volts from the Fermi energy. The absence of a sudden drop on the differential CVCs at |U| →0 is a clear evidence that the bulk electrons don't make any appreciable contribution to the tunneling current and the latter is completely due to the surface electrons.

The foregoing reasoning demonstrates that the observed finite density of states at the Fermi level and all singularities in the voltage range of approximately -0.5 to +0.5 V are associated only with surface electrons states. A two-dimentional layer of metal with normal metallic density of conducting electrons states exists on bismuth surface. These results give an extensive and prominent experimental material for theoretical studies related to the calculations of electronic structure of two-dimensional systems.

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