Inelastic low-energy electron diffraction by the antimony (111) surface

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A narrowing of a reflection corresponding to inelastic low-energy electron diffraction with respect to the corresponding reflection of elastic low-energy electron diffraction has been discovered. This contraction is of a resonant nature in the electron energy. The directions of the elastic and inelastic diffraction peaks are the same. The observations are explained in terms of a resonant capture of an incident electron to a surface state [E. G. McRae, Rev. Mod. Phys. **51**, 541 (1979)].

The angular distribution of electrons which are reflected inelastically with a small energy loss ($\lesssim 50$ eV) from a solid surface is known to be sharply nonmonotonic and reminiscent of the pattern of elastic low-energy electron diffraction (LEED) (Ref. 2, for example). In the present letter we report several results from measurements on the structure of the reflections during elastic and inelastic LEED by an antimony surface.

The structure of the reflections is measured with the help of a fast, computer-controlled LEED data acquisition and processing system.[3] This system can determine $I(\theta,\varphi,E_T)$, the angular distribution of the electrons with energies $E > E_T$ which are reflected from the surface; θ and φ are the polar and azimuthal angles, respectively. In contrast with apparatus used previously, this system can carry out a rapid analysis of the angular distribution of the inelastically reflected electrons over a broad solid angle. The angular distribution is reconstructed from an analysis of an optical image of the diffraction pattern on the fluorescent screen of a standard four-grid analyzer. The energy E_t is determined by the voltage on a retarding grid. The experimental data are reported in the form of the quantities

$$I_{\rm el} = I(\theta, \varphi, E_p - \Delta_1),\ I_{\rm in} = I\left(\theta, \varphi, E_p - E_{\rm sp} - \frac{\Delta_2}{2}\right) - I\left(\theta, \varphi, E_p - E_{\rm sp} + \frac{\Delta_2}{2}\right),$$

where E_p is the energy of the electrons of the incident beam, $I_{\rm sp}$ is the energy of a surface plasmon in antimony, and Δ_1 and Δ_2 are given energy gaps, which are chosen in such a way that $I_{\rm el}$ and $I_{\rm in}$ correspond to the angular distributions of the electrons which are reflected elastically from the surface of the sample and the electrons which have lost some energy E_{sp}, with a reasonably high signal-to-noise ratio. From I_{el} and I_{in} we subtract the component of the background that varies smoothly over θ and φ. We use a Rieber ultrahigh-vacuum apparatus, fitted with a low-energy electron diffractometer, Auger and mass spectrometers, and a sample preparation chamber. The test surface is produced by cleavage and cleansed by heating. The working pressure in the chamber is $\sim 10^{-9}$ torr (Ref. 3).

Earlier studies had shown (see, e.g., Ref. 4 and the bibliography there) that inelastic LEED can be described by a two-step model: elastic diffraction with an inelastic energy loss before (or after) the diffraction. Inelastic LEED occurs because the differential scattering cross section is highly elongated in the forward direction. The experimental arrangement used by us has the distinctive feature that the loss due to the production of surface plasmons before diffraction is eliminated by conservation of energy and of the tangential component of the momentum. The situation is explained by Fig. 1. In terms of this two-step model, the possible states during inelastic LEED are the states $\mathbf{P}'_{\pm}$, to which an electron goes from the states $\mathbf{P}_{\pm}$, having emitted a surface plasmon with a momentum $\pm \mathbf{P}_{\mathrm{sp}}$. The energy of a bulk plasmon in antimony is[5] 16 eV, and the corresponding energy of a surface plasmon is 11 eV. A displacement of the inelastic-LEED reflection from the corresponding elastic-LEED reflection should occur in the direction of the specular peak, and it should decrease with increasing E_p. At small values of E_p, this energy dissipation mechanism should cease to operate, when $\mathbf{P}_{\mathrm{sp}}$ (Fig. 1) reaches a critical value.[6] These are precisely the features of inelastic LEED which we observe for the various reflections. Figures 2 and 3 show experimental data on I_{el} and I_{in} near the (02) and (03) reflections for the case in which the electron beam is incident normally on the surface. At $E_p \lesssim 80$ eV, there are no inelastic-LEED reflections; in the interval $E_p \approx 100$–200 eV there are substantial differences in the positions of the reflections of elastic and inelastic LEED, as can be seen in Fig. 2 (the reflections on the right correspond to inelastic LEED). At high energies, the inelastic LEED occurs, but the positions of the inelastic-LEED reflections are essentially the same as those of the elastic-LEED reflections. At $E_p = 306$ eV (Fig. 3) we observe no differences in the spatial direction for the elastic and inelastic reflections, but there is a significant narrowing of the inelastic reflection in comparison with the corresponding elastic reflection.

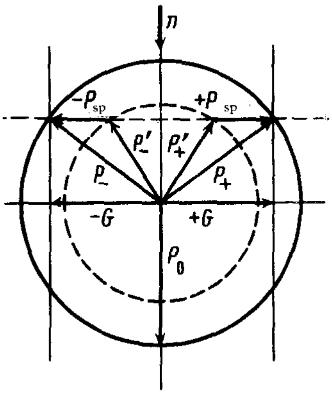

FIG. 1. Diagram of the two-step inelastic LEED. **G**—Reciprocal-lattice vector of surface; $\mathbf{P}_0$—momentum of the electrons incident on the surface; $\mathbf{P}_{\pm}$—momenta of the diffracted electrons; **n**—normal to the surface of the sample; circles—constant-energy surfaces for the energies E_p and $E_p - E_{\mathrm{sp}}$.

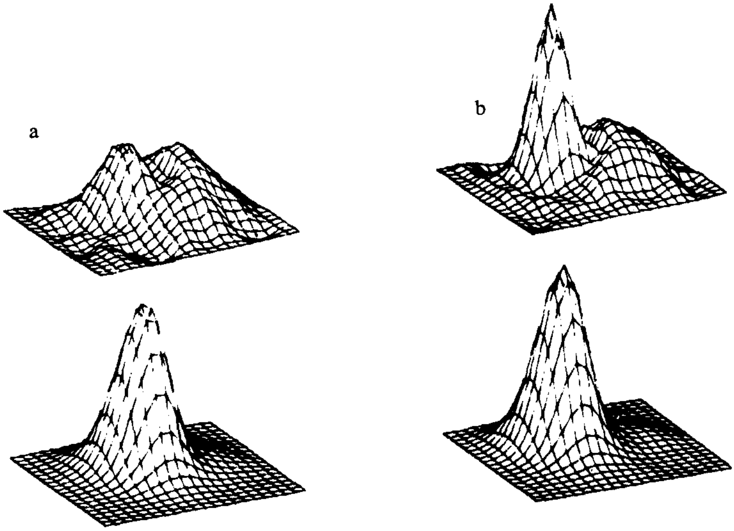

FIG. 2. Structure of the (02) reflection of elastic (bottom) and inelastic LEED. The intensity is plotted in arbitrary units along the ordinate axis (the scale is ten times larger for the inelastic reflection). The tangential component of the wave vector of the reflected electron is plotted along the abscissa axes (0.05 Å^{-1}/div). The origin is displayed to the right of the elastic reflection. $\Delta_1 = \Delta_2/2 = 2$ eV. a—$E_p = 120$ eV; b—$E_p = 116$ eV.

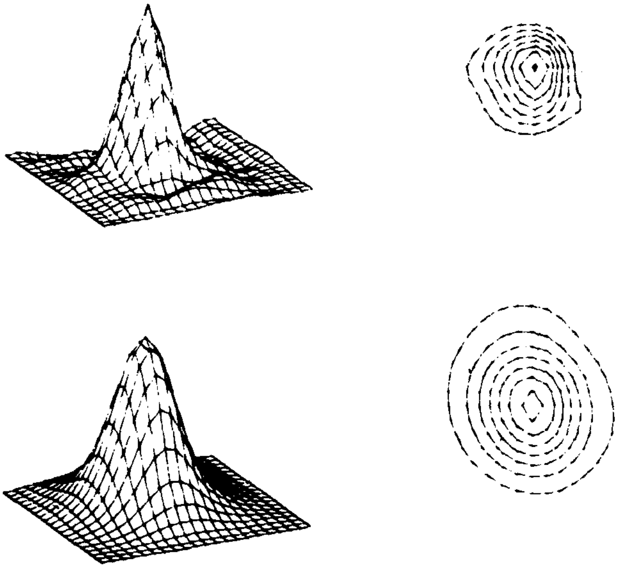

FIG. 3. Structure (at the left) and constant-intensity levels projected onto the plane of the sample during elastic (at the bottom) and inelastic LEED for the (03) reflection. The intensity is plotted in arbitrary units along the ordinate axis (the scale is five times larger for the inelastic reflection). The tangential component of the wave vector of a reflected electron is plotted along the abscissa axes (0.08 Å^{-1}/div). The origin is displaced to the right of the elastic reflection. $\Delta_1 = \Delta_2/2 = 2$ eV.

The inelastic LEED has two interesting features: 1) the existence of an inelastic-LEED reflection which coincides in direction with the corresponding elastic reflection and which is a strong function of E_p (Fig. 2); 2) the circumstance that the angular width of the inelastic (03) peak is significantly smaller than that of the elastic (03) peak (Fig. 3).

These features can be explained on the basis of the concept of an electron surface resonance.[1] At certain resonant values of E_p, an incident electron is captured to a surface state. The resonant value of E_p is given quite accurately by $E_p = \epsilon_n + \mathbf{G}^2/2m_e$, where $\mathbf{G}$ is the reciprocal-lattice vector of the surface, ϵ_n is the energy level of the surface state, and m_e is the effective mass of the electron. The inelastic LEED occurs in the following way: An electron incident normally on the surface is captured to a surface-resonance state. A surface plasmon is then radiated, and an electron is emitted into a vacuum. The probability for emission in a direction near the elastic-LEED reflection (with a small change in the tangential component of the momentum, eliminating a change in the reciprocal-lattice vector) is relatively high, in particular because of the high state density of plasmons near a zero momentum. According to this model, the narrowing of the inelastic-LEED reflection is due to the resonant nature of the capture to the surface state,[1] which leads to an effective narrowing of the spectrum and a decrease in the angular divergence of the primary beam. In addition to the proposed resonance, there is obviously also a nonresonant scattering because of the electron-electron and electron-phonon interactions,[7] which tend to erase the observable features in the inelastic LEED.

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