Effect of surface states on the surface scattering of current carriers

O. A. Panchenko and S. V. Sologub
Institute of Physics of National Academy of Sciences of Ukraine, Prospekt Nauki 46, UA-03028, Kiev-28, Ukraine
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This Brief Report reports experimental evidence that electron transitions between surface and bulk states provide an effect on the conductivity of a metallic plate.

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Surface scattering of current carriers can provide a considerable effect on the transport properties of thin films and nanostructures. The effect gets more pronounced as conductor dimensions decrease. Surface scattering has been studied by many authors both theoretically and experimentally.[1–3] Its nature is governed by the crystallographic structure of the surface lattice, surface impurities, symmetry of the two-dimensional adsorbate lattice, and the topology of the conductor Fermi surface. Electron collisions with the surface can induce transitions between bulk and surface electron states and thus also modify the character of surface scattering. With no other scattering mechanisms being involved, transitions between surface and bulk electron states are determined by the conservation of energy and tangential component of the quasimomentum, i.e.,

$$\varepsilon = \varepsilon' = \varepsilon_F, \tag{1}$$

$$\mathbf{k}_t = \mathbf{k}_t' + n\mathbf{g}, \tag{2}$$

where ε is the carrier energy, ε_F is the Fermi energy, $\mathbf{k}_t$ is the wave-number tangential component, $\mathbf{g}$ is the surface reciprocal lattice vector, and n is an arbitrary integer, primed and nonprimed quantities correspond to the carrier states before and after scattering, respectively.

In this case the surface scattering depends both on the topology of the projection of the bulk-crystal-carriers' Fermi surface onto the surface crystallographic plane, and on the topology of surface-electron-state Fermi contours in the same plane. Actually, surface scattering is the same as electronic-wave diffraction at the surface lattice of the conductor. On the other hand, the topology of the Fermi contour depends on the surface lattice symmetry which may undergo changes in the course of surface phase transitions.

One may control the surface scattering through adsorption, ordering, and modifying the concentration of adsorbed submonolayer films and reconstruction of the surface. The kinematic analysis of carrier transitions suggests important conclusions concerning the nature of surface scattering even with the modifications of the surface electronic structure being disregarded.[2,3] The experiments have been performed mainly for carriers that fill energy states in the bulk metal.[1–3] Relatively recent studies have dealt with the effect of surface-state-carrier scattering by adsorbed atoms and atomic-scale surface steps. Specifically, they have observed the appearance of standing electronic waves and an impressive phenomenon-formation of quantum corrals.[4–7] As follows from these experiments, the estimated value of specularity for the reflection of surface electrons is as low as about 0.3, whereas specularity associated with bulk carriers can be close to one.[2,3] An important study concerning the influence of surface scattering on the charge transfer along the metal surface has been provided by the experiment on the electronic focusing of carriers and the observation that bulk electrons can be captured into surface resonance levels.[2]

We have shown experimentally that, for an atomically pure surface of W(110), a change of the topology of the surface-state Fermi surface under the adsorption of an ordered hydrogen or deuterium monolayer produces an increase of specularity of the surface carrier scattering associated with the reduction of available transition channels between bulk and surface states.

The experiments were performed in an UHV glass device at the residual pressure about 10^{-11} Torr and liquid-helium temperature. We applied a new surface-sensitive method based on a galvanomagnetic size phenomenon called the static skin effect.[3] The effect is observed when a strong magnetic field is applied in the plane of the sample-plate surface perpendicular to the current under the condition $r_H \ll l$, where r_H and l are the Larmor radius and current-carrier mean free path in the bulk conductor, respectively. In order to weaken the influence of scattering mechanisms other than the surface one, we have used a high-purity W(110) plate cooled to the liquid-helium temperature (the ratio of electrical conductivities for the room and liquid-helium temperatures being 10^{-5} to 10^{-6}). The surface of a plane-parallel plate with dimensions about $4\times8\times0.1$ mm^3, oriented in the plane (110) up to 0.05° precision, was treated by means of the standard procedure.[3] In experiments the plate transversal magnetoresistance (MR), i.e., the value $[R(H)-R(0)]/R(0)$, was investigated, where $R(H)$ and $R(0)$ are the resistance in a strong magnetic field and electrical resistance, respectively. For the high-purity single-crystal plate at the liquid helium temperature in a strong magnetic field the expression $R(H) \gg R(0)$ is valid[3] and the value $R(0)$ can be neglected. The constant magnetic field strength was about 15 kOe.

Deposition of a hydrogen or deuterium submonolayer film on the surface of a W(110) plate under the conditions of static skin effect leads to nonmonotonic changes of the plate MR (the left-hand part of Fig. 1). The dependence, measured for $T=4.2$ K and constant adsorbate flux to the surface, shows that the character of the current-carrier surface scattering is modified as the adatom surface concentration increases from zero (for an atomically pure surface) to the saturation-coverage value. The after-annealing of the depos-

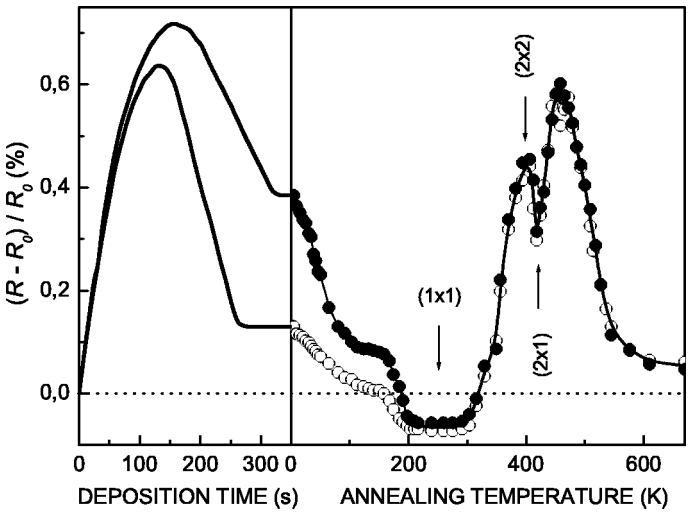

FIG. 1. MR changes for a W(110) plate under hydrogen and deuterium adsorption, $T=4.2$ K (upper and lower curves in the left-hand part, respectively) and under the annealing of saturated deposited adsorbate films (empty circles—hydrogen, filled circles—deuterium). Arrows indicate the regions of maximum development of the two-dimensional adsorbate lattices. R_0 is MR of the plate with atomically pure surfaces.

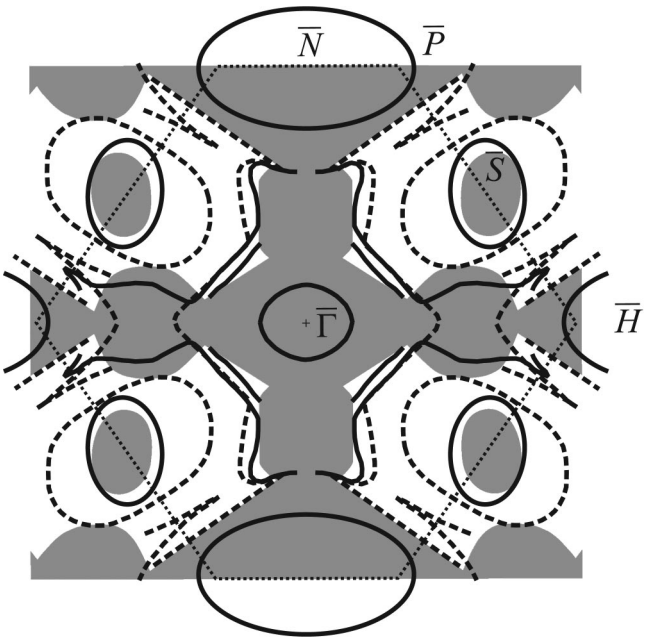

FIG. 2. Shadow projection of the tungsten Fermi surface onto the (110) plane (gray region) and the structure of the surface electron states for the W(110) face: dashed lines—the surface is covered with an ordered hydrogen monolayer, solid lines—atomically pure surface (Ref. 10).

ited film at growing temperatures changes the adsorbate concentration and induces ordering of chemisorbed submonolayer structures which modifes the character of current-carrier surface scattering by virtue of the electron-hole transfer. These processes are manifested in the nonmonotonic dependence of the MR under the annealing of the adsorbed film (the right-hand part of Fig. 1).

The $T \approx 200-300$ K plateau in Fig. 1 indicates that the character of surface scattering is not modified in this annealing-temperature range, this fact being the evidence for unchanged concentration and symmetry of the adsorbed film. Structural studies by means of the low-energy electron diffraction method show that in this range of annealing temperatures, there exists an adsorbate monolayer with the highest degree of order. It should be noted that the MR value associated with such films is *lower than the MR of a plate with an atomically pure surface*. In other words, *ordering of an atomic hydrogen or deuterium monolayer increases the specularity of current-carrier surface scattering*. At first sight, this effect seems to be strange. Hydrogen adsorption on a W(110) surface does not lead to the reconstruction of the tungsten surface.[8] However, even if the atomic monolayer of the adsorbate is completely ordered and reproduces the (1×1) structure, both the adatom-lattice shift in the surface plane with respect to the lattice of the upper layer of substrate atoms and the difference of the effective scattering cross sections for adatoms and tungsten atoms additionally contribute to the diffuseness of the surface scattering. Moreover, the monolayer film on this face is known to have domain structure due to the existence of two equivalent adcenter types with threefold coordination.[8] Scattering from domain walls also decreases the specularity of carrier reflection. The above reasons can only violate the coherence of current-carrier scattering and hence cannot lead to an increase of the specularity of surface scattering thereof that results in the MR decrease.

The reason for the effect becomes clear as one analyzes the changes of the electron structure of surface states in the course of hydrogen monolayer adsorption. The results for a W(110) surface obtained by means of angle-resolved photoelectron spectroscopy are given in Fig. 2.[9,10] The figure shows the projection of the Fermi surface of bulk electron states of tungsten onto the (110) plane and experimental Fermi contours of the surface states for an atomically pure surface (solid lines in Fig. 2) and for a surface covered with an ordered atomic-hydrogen monolayer (dashed lines in Fig. 2).

According to the conservation laws (1) and (2), the transitions between surface and bulk states can occur provided the projections of the relevant parts of the Fermi surface overlap (or differ by a linear combination of the surface reciprocal lattice vectors). As follows from Fig. 2, in the case of the atomically pure W(110) surface there can occur direct or "vertical" carrier transitions between surface and bulk states. The conservation law (1) is satisfied because both bulk and surface electron states energies are equal to ε_F with an accuracy to kT. Thus transitions are allowed between the elliptic Fermi contours centered at points $\overline{\Gamma}$ and $\overline{N}$ of the surface Brillouin zone and, respectively, between the electron jack and hole octahedron of the bulk Fermi surface. It is highly probable that such transitions accompany the surface scattering of carriers and thus provide a specific version of the multichannel specular scattering of carriers at a conductor surface.[3]

Adsorption and ordering of the monolayer hydrogen film result in the disappearance and transformation of some Fermi

contours of surface states (solid lines in Fig. 2) and the appearance of other Fermi contours (dashed lines in Fig. 2). The Fermi contours are "pressed out" from the ranges of projections of the bulk Fermi surface. By virtue of relation (2), transitions between surface and bulk states are forbidden in this case; hence the specularity of the carrier surface scattering increases. The value of the effect, i.e., the MR change, is not large because the phase volume occupied by the surface states is relatively small.

Thus an atomically pure surface of W(110) scatters carries more diffusely than a surface covered with an ordered hydrogen or deuterium monolayer. Comparing our data with the data on the changes of the topology of the surface-state Fermi contour on the W(110) surface suggests a conclusion that a surface-scattering specularity increase under the formation of a hydrogen monolayer is produced by the reduction of available transition channels between bulk and surface states.

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