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Effect of surface electron structure variations on the surface scattering of current carriers

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An effect of electron transitions between the surface and bulk electron states on the conductance of a $W(110)$ metal plate has been observed in experiment for the first time using the static skin-effect and transversal magnetoresistance methods.

Впервые экспериментально наблюдалось влияние электронных переходов между носителями поверхностных и объемных электронных состояний на проводимость металлической пластины $W(110)$ с помощью методов статического скин-эффекта и поперечного магнетосопротивления.

The surface scattering of current carriers influences significantly the transport properties of thin films and nanostructures. Its importance increases as the conductor size diminishes. The surface scattering was studied in numerous experimental and theoretical works [1–3]. Its character is defined by the surface lattice crystallography, the presence of surface impurities, the symmetry of the 2D lattices of the adsorbate and the topology of the conductor Fermi surface. Collision of electrons with the surface may result in transitions between the bulk and surface electron states, that changes also the surface scattering character [4]. Other scattering mechanisms being absent, the transitions between the bulk and surface electron states are defined by the conservation laws of quasi-momentum energy and tangential component:

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

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

where ε is the carrier energy; ε_F, the Fermi one; $\mathbf{k}_t$, the wave number tangential component; $\mathbf{g}$, the surface reciprocal lattice vector; n, an arbitrary integer; primed and unprimed quantities refer to the carrier state prior to and after the scattering, respectively. In this case, the surface scattering depends on the topology of the conductor bulk carriers Fermi surface projection onto the surface crystallographic plane as well as on the topology of the Fermi contours of surface electron states for the specific crystal face. The surface scattering is in essence the electron wave diffraction on the conductor surface lattice. The Fermi contour topology depends, in turn, on the surface lattice symmetry that may undergo changes due to the surface phase transitions.

The possible ways to effect in a controllable manner the surface scattering include adsorption, ordering and concentration variations of the adsorbed submonolayer films, and the surface reconstruction. Even when the adsorption-induced changes in the surface electron structure are not taken into account, the kinematic consideration of the carrier transitions provides some important conclusions on the surface scattering character [2, 3]. The experimental studies concerned mainly the carriers of the bulk metal states [1–3]. Recently enough, the effects of surface state carrier scattering on adsorbed atoms and on the atomic scale surface steps have been studied. In particular, formation of the electron standing waves was observed as well as an impressive effect of the quantum corals formation [5–8]. Those experiments made it possible to estimate the re-

flectivity coefficient for the surface state electrons that is found to be as low as about 0.3, while that quantity may be about 1 for the bulk carriers [2, 3]. The experiment aimed at the carrier electronic focussing where the bulk state electrons were observed to be trapped at the surface resonance levels is an investigation of importance concerning the problem of the surface scattering part in the charge transfer along the metal surface [2].

We have shown in experiment that a change in the Fermi contour topology of the sufrace state of atomically pure W(110) surface due to adsorption of an ordered hydrogen or deuterium monolayer results in an increased specularity of the carrier surface scattering caused by reduction of possible transition channels between the bulk and surface states.

The experiments were carried out in a ultrahigh vacuum glass apparatus at the residual pressure of 10^{-11} Torr and liquid helium temperature. The home-developed surface-sensitive methods were used basing on galvanomagnetic size phenomena, namely, static skin-effect and transversal magnetoresistance [3]. The static skin-effect is observed in a strong magnetic field applied in the surface plane of the film sample and perpendicular to the running current under condition that $r_H << l$, where r_H and l are the Larmor radius and mean free path of the current carriers in the bulk conductor. If the applied magnetic field is perpendicular to the plate surface, then, the strong magnetic field condition being met, the surface magnetoresistance takes a surface sensitivity, too. To eliminate the effects of other scattering mechanisms except for the surface one, a high-purity W(110) plate cooled down to the liquid helium temperature. The bulk electric resistance ratio at room and helium temperatures was about 10^5 to 10^6. The surface of the plane-parallel plate of about $4\times8\times0.1$ mm^3 size oriented in the (110) plane to within 0.05° was treated to the atomically pure state using a standard procedure [2]. The constant magnetic field strength was in the 15 to 30 kOe range.

The deposition of a hydrogen or deuterium submonolayer film onto the W(110) plate under the static skin-effect conditions results in a non-monotonous variation of the plate magnetoresistance (MR) (see Fig. 1, left side). This dependence (measured at $T = 4.2$ K and a constant adsorbate flow to the surface) demonstrates the character variation of the current carrier surface scattering as

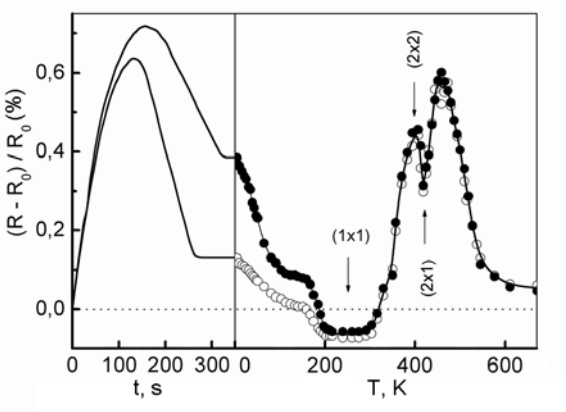

Fig. 1. MR variation of a W(110) plate at hydrogen and deuterium adsorption ($T = 4.2$ K) (upper and lower curves in the left-hand part of the figure, respectively) and at annealing of saturated adsorbate films (open circles, hydrogen; solid circles, deuterium). The arrows show the areas of maximum development of 2D adsorbate lattices. R_0 is the MR at atomically pure surface.

the surface concentration of the adatoms increases from the atomically pure surface to the saturated coating. The subsequent annealing of the deposited film at increasing temperatures results in changes of the adsorbate concentration and in formation of ordered chemisorbed submonolayer structures that change the character of current carrier surface scattering, in particular, due to the electron-hole transfers. Those processes (demonstrated by the non-monotonous MR dependence at the film annealing) have been studied by us before [2].

The plateau in the $T \approx 200$ to 300 K range (see Fig. 1) shows that the surface scattering character remains unchanged in this range of the annealing temperature, thus evidencing the constant concentration and symmetry of the adsorbed film. The structure studies by LEED show that at those annealing temperatures, the adsorbate monolayer is maximally ordered. It is to note that the MR value corresponding to such films is lower than that for the atomically-pure plate surface. In other words, the ordering of the atomic hydrogen or deuterium monolayer increases the specularity of current carrier surface scattering. This effect is strange at first glance. Hydrogen adsorption on the W(110) surface does not result in the tungsten surface reconstruction [9]. Nevertheless, even if the adsorbate atomic monolayer is completely ordered and repeats the (1×1) structure, the lattice of the adatoms is shifted relatively to that of

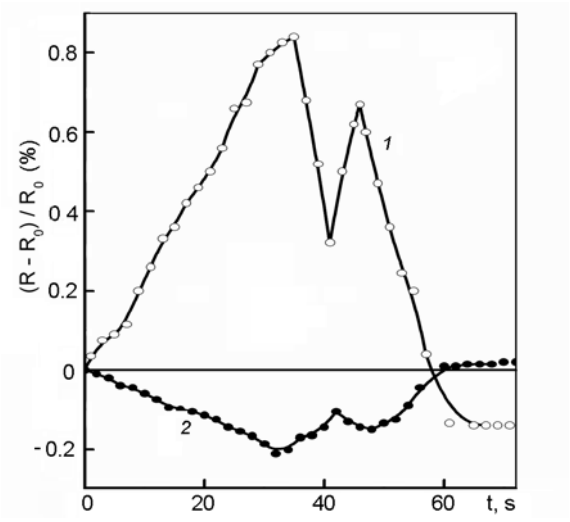

Fig. 2. MR variation of a W(110) plate at hydrogen adsorption (T = 200 K). The magnetic field is directed parallel (open circles) and perpendicular (solid circles) to the plate surface. R_0 is the MR at atomically pure surface.

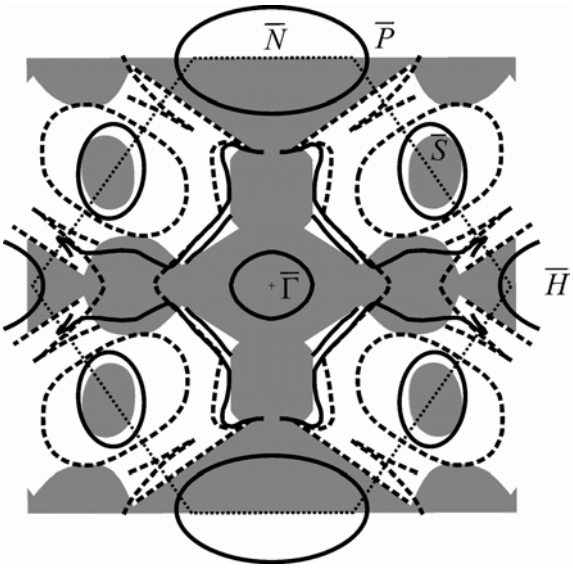

Fig. 3. Shadow projection of the Fermi surface for tungsten on the (110) plane (shadowed area) and the structure of the electron surface states for the W(110) face. Dashed lines relate to the surface coated with ordered hydrogen monolayer; solid lines, to atomically pure surface [9, 10].

the upper layer of the substrate atoms. Moreover, the effective scattering cross-sections of the adatoms and tungsten atoms are different. These factors contribute additionally to the surface scattering diffuseness. In addition, the monolayer coating is known to have a domain structure, because two equivalent adsorption center types with three-fold coordination coexist at this face [9]. The scattering from the domain walls decreases also the specularityof the carrier scattering. The factors listed above may only distort the carrier scattering coherency and thus are unable to cause the reflectivity increase that results the lowered MR.

The above effect is observed also at hydrogen deposition onto the heated substrate. The results of those studied are shown in Fig. 2 for two directions of the magnetic field. Both under the static skin-effect conditions (the magnetic field is parallel to the surface) and at the magnetic field perpendicular to the sample surface (the transversal MR is measured), the MR value for the adsorbate monolayer is lower than that for the atomically-pure surface. The mirror symmetry of curves in Fig. 2 demonstrates the surface nature of the phenomenon. The magnetic field direction was varied around the (100) direction of the tungsten single crystal. That direction is a four-fold symmetry axis, therefore, those magnetic field direction are physically equivalent in relation to the crystal bulk.

The effect cause is elucidated by considering the changes in the electron structure of surface states accompanying the hydrogen adsorption. The results of those investigations for the W(110) surface obtained using the photoelectron spectroscopy with angular resolution are shown in Fig. 3 [10, 11]. The figure presents the projection of Fermi surface of the bulk electron states in tungsten on the (110) plane as well as experimental Fermi contours of the surface states for an atomically pure surface (solid lines) and that coated with ordered monolayer of atomic hydrogen (dashed lines).

According to conservation laws (1, 2), transitions between the surface and bulk states are possible when the corresponding projections of the Fermi surface parts are overlapped (or differ from one another by a linear combination of the surface reciprocal lattice vectors). It follows from Fig. 3 that direct or "vertical" transitions are possible for the atomically pure W(110) surface. The energy conservation law (1) is met because both bulk and surface electron states have the same energy ε_F to within kT. For example, permitted are transitions between the elliptic Fermi contours centered at the points $\overline{\Gamma}$ and $\overline{N}$ of the surface Brillouin zone and, respectively, between the electron jack and the hole octahedron of the bulk Fermi surface. Such transitions are highly probable at the surface scattering of carriers. Those are a kind of multichannel specular

reflection of carriers at the conductor surface [3].

The adsorption and ordering of a monolayer hydrogen film results in disappearance of some Fermi contours of surface states (solid lines in Fig. 3) and appearance of other ones (dashed lines). The Fermi contours become "squeezed out" from the projections of the bulk parts of the Fermi surfaces. By virtue of Eq.(2), the transitions between the bulk and surface states are forbidden in this case, thus, the surface reflection of carriers becomes more specular-like. The small value of the effect, i.e., of the MR change, is due to the relatively small phase space occupied by the surface states.

Thus, the atomically pure W(110) surface scatters the carriers in a more diffuse fashion that the same surface coated with an ordered monolayer of hydrogen or deuterium. Comparison of our data with those on the topology changes of the Fermi contours of surface states at the hydrogen adsorption on the W(110) surface gives rise to the conclusion that the increased specularity of the surface scattering at the hydrogen monolayer formation is caused by reduction of possible transition channels between the bulk and surface states.

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Вплив зміни поверхневої електронної структури на поверхневе розсіювання носіїв струму

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Вперше експериментально спостерігався вплив електронних переходів між носіями поверхневих і об'ємних електронних станів на провідність металічної пластини *W*(110) за допомогою методів статичного скін-ефекту та поперечного магнітоопору.