Phonon-drag observation of topological transitions in a 2D Fermi system

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A study has been made of the phonon drag of surface charges in silicon metal-insulator-semiconductor structures fabricated on planes making an angle of 9° to 10°40′ with the (001) face. The dependence of the phonon drag on the surface charge density N_s is complicated and has some strikingly large structural features which correspond to topological changes in the Fermi surface of the 2D charges. The size of the minigap in the electron spectrum is determined.

Since the 2D electron systems which arise in inversion layers on surfaces tilted from the basis surface have a complicated dispersion law (see the review by Volkov *et al.*[1]), these surfaces make it a simple matter to induce Lifshitz topological transitions[2] in 2D Fermi systems by varying N_s.

This letter reports the first experimental observation of a change in the phonon drag of the charges of a 2D system during topological transitions. We have observed the appearance of singularities at these transitions. The possible appearance of structural features of this type has been discussed in several theoretical papers for the 3D case (see § 10 in Ref. 2).

We studied metal-insulator-semiconductor structures grown by the standard technique on silicon surfaces making angles of $\theta = 9°$, 9°27′, 10°, and 10°40′ with the (001) plane. As in some earlier experiments,[3] we used a comparison method to measure the electric field (E_{ph}) which arises along the inversion layer at a constant flux density of nonequilibrium phonons, W. We studied the ratio $E_{ph} W^{-1}$, which is a measure of the phonon drag of the charges. The diffusion part of the thermoelectromotive force was slight under these experimental conditions.[3] The measurements were taken at several voltages across the gap, V_g. We recall that the surface charge density is

$$N_s = C(V_g - V_0)/e|^{-1},$$

where e is the elementary charge, V_0 is the threshold voltage, and C is the capacitance per unit surface area, determined experimentally.

Figure 1 shows some typical curves of $E_{ph} W^{-1}$ vs V_g. These curves correspond to the two samples with the smallest and largest angles θ. We can clearly see some structural features ("singularities"), the most important of which are marked "*A*" and "*B*." The heights of these structural features and their sharpness both increase with decreasing measurement temperature. Structural features were observed for all the samples studied. Their nature does not depend on the charge mobility, which ranged from 8.3 to 19×10^3 cm^2/(V·s). Although the detailed properties of these structural

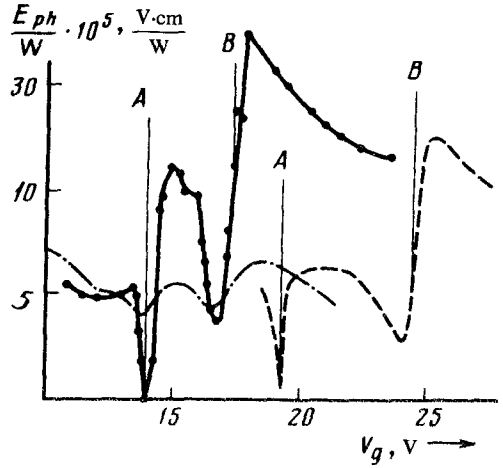

FIG. 1. Phonon drag in an inversion metal-insulator-semiconductor channel of a structure fabricated on a plane tilted at an angle $\theta = 9°$ or 10°40′ from the (001) face. For the sample with $\theta = 9°$: $V_0 = -1$V, $N_s = 1.6 \times 10^{-11}(V_g - V_0)$ $V^{-1} \cdot cm^{-2}$. For the sample with $\theta = 10°40'$: $V_0 = -1.3$ V, $N_s = 1.76 \times 10^{11}(V_g - V_0)$ $V^{-1} \cdot cm^{-2}$. Solid curve—$\theta = 9°$, $T = 0.7$ K; dot-dashed curve—$\theta = 9°$, $T = 1.9$ K; dashed curve—$\theta = 10°40'$, $T = 0.7$ K.

features can vary from sample to sample (as can be seen from a comparison of the two curves in Fig. 1), the general nature of the structural features remains the same. The results in Fig. 1 show the behavior of $E_{ph} W^{-1}$ in the case of a heat flux along the angle at which the surface is tilted.These structural features remain in the case of a perpendicular heat flux, but they change considerably in nature (especially A).

Let us compare these results with the electron spectrum of the metal-insulator-semiconductor structures. We know[1] that a long crystallographic period for translation along the surface arises on a crystal surface with high Miller indices. This period causes radical changes in the electron spectrum; in particular, for the electrons of surfaces near (001) the **k**-space degeneracy is lifted: The centers of the projections of the electron valleys are displaced $0.85(2\pi/a)\sin\theta$ (a is the lattice constant of Si) from the center of the Brillouin zone. Figure 2 is a sketch of the band structure which arises near the boundary of the 2D Brillouin zone. It is easy to see that two topological transitions occur as the surface charge density is changed: Two separate Fermi surfaces coalesce (A), and a new band forms (B). These transitions are separated because of the discontinuity of the spectrum at the zone boundary and the formation of a minigap Δ.

These structural features of the spectrum can obviously be compared with the results of the phonon-drag measurements (Fig. 1). The substantial decrease in the drag at A, for example, is caused by electron-phonon scattering accompanied by transitions between surfaces separated by the boundary of the Brillouin zone. After these surfaces subsequently coalesce through the formation of a bridge, the decrease in the drag results from the interaction of phonons with bridge electrons, whose effect also has a sign[4] opposite that of the bulk of the Fermi surface. With increasing size of the bridge, the absolute value of its contribution decreases. All these events are responsible for the

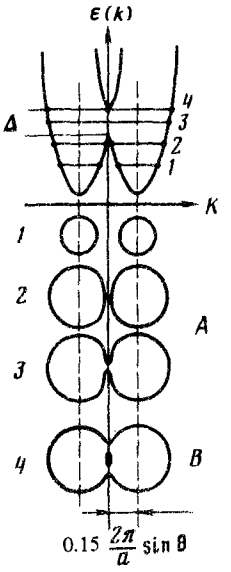

FIG. 2. Dispersion law for 2D charges on a tilted surface. Vertical solid line—Boundary of the Brillouin zone; dashed lines—centers of valleys. Shown at the top is a section through $\epsilon(k)$ in a plane perpendicular to the metal-insulator-semiconductor structure; shown at the bottom are constant-energy contours in the plane of the metal-insulator-semiconductor structure.

sharpness of structural feature A. One more piece of evidence that A corresponds to the coalescence of two Fermi surfaces (or "Fermi curves" in this 2D case) is that the radius vector of the Fermi surface $\mathbf{k}_{FA}$ calculated from $N_s(A)$ is equal to $0.15\ (2\pi/a)\sin\theta$—the distance from the center of the Fermi surface to the boundary of the Brillouin zone. (In none of the eight samples studied did the difference between k_{FA} and $0.15(2\pi/a)\sin\theta$ exceed 2%.

The second structural feature, B, is apparently due to the formation of a new Fermi surface at the boundary of the Brillouin zone (4 in Fig. 2). The reason for the complex shape of this feature is that initially at $k_F \ll q$, where q is the phonon wave vector, the zone which has appeared leads to only a scattering of phonons; only after it has increased in size to $k_F \geqslant q/2$ does it lead to an additional contribution to the phonon drag exerted on the charges. Working from the average state density of 2D electrons, $D = 1.6\times 10^{14}\ \mathrm{V}^{-1}\ \mathrm{cm}^2$, and the values of N_A and N_B, we can estimate the size of the minigap (Δ) in the electron spectrum. The results found for Δ increase smoothly from 3.4 to 6 meV with increasing angle θ, in agreement with the results of other determinations of this quantity.[1]

In summary, the complicated behavior of the phonon drag as a function of N_s in inversion layers tilted at an angle from the (001) face can be explained at least qualitatively in terms of topological transitions in this 2D Fermi system. A further analysis of all the results on the phonon drag exerted on charges, combined with a theoretical analysis of the phenomenon, will undoubtedly reveal additional aspects of the changes in the electron spectrum caused by the presence of a superperiod. We hope to return to this question in a future paper.

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