Phonon-electron interaction in silicon inversion layers

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The phonon drag of charges in p and n inversion layers on silicon has been studied. The phonon-electron interaction has been found to intensify by a factor of several units at $q \simeq 2K_F$, probably because of the two-dimensional nature of the system. The strain energy in an inversion channel is determined.

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The surface charge density N_s in an inversion layer in a metal-insulator-semiconductor structure can be controlled by varying the gate voltage.[1] This circumstance opens up some new opportunities for using the phonon drag α_{ph} of charges to study the phonon-electron interaction. The distribution of nonequilibrium phonons in the case of a thin conducting layer is determined exclusively by the characteristics of the body of the silicon wafer, so that the phonon drag in a two-dimensional ($2D$) system is directly proportional to the interaction of the phonons with electrons.[2]

The metal-insulator-semiconductor structures were fabricated by the standard technology: an n-type layer on a silicon [100] surface and a p-type layer on a silicon [111] surface. The maximum mobility in the n-type layer was $\mu = 1.5 \times 10^4$ cm^2/(V·s), while that in the p-type layer was $\mu = (1.1\text{–}1.5) \times 10^3$ cm^2/(V·s). Lead–tin superconducting leads were soldered to the structures for measuring the thermal emf. The measurements of α were made by a comparison method, as in Ref. 2, with a quantum interferometer used as a null detector in the circuits for measuring ΔT and U.

Figure 1 shows the measurements of the thermal emf α of the conducting inversion layers. The value of α is several orders of magnitude higher than the thermal emf

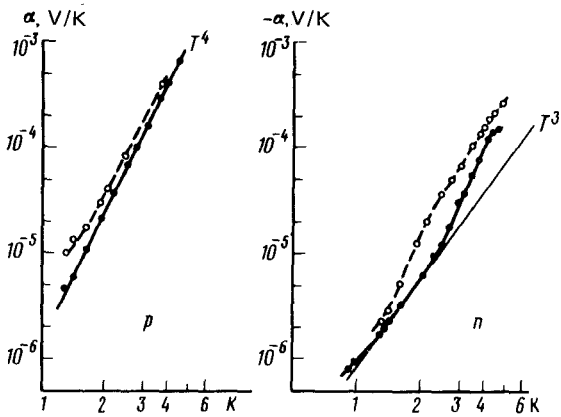

FIG. 1. Thermal emf of metal-insulator-semiconductor structures. Filled circles—$N_s = 4.5 \times 10^{12}$ cm^{-2} for the n-type structure or $N_s = 4.1 \times 10^{12}$ cm^{-2} for the p-type structure; open circles—$N_s = 4.1 \times 10^{12}$ cm^{-2}.

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which is customarily observed both in metals at low temperatures and in conducting germanium films.[2] The emf α is generated primarily by the phonon drag of charges, α_{ph}. The diffusion component α_e is insignificant. From the experimental results we conclude $\alpha_e \lesssim 10^{-6}$ T (volts per kelvin).

Let us first take a more detailed look at the characteristics of the n-type samples. Their thermal emf is proportional to T^3 only at low temperatures—below 2.7 K for a sample with $N_s = 4.5\times 10^{12}$ cm^{-2}, for example. At higher temperatures we find a complicated dependence $\alpha_{ph}(T)$. At the same time, we find $q\Lambda \gg 1$ for these samples [$q(T)$ is the wave vector of the phonon corresponding to the maximum of the Planckian distribution of thermal phonons, and Λ is the mean free path of the charges]. In this case, according to our understanding of phonon drag, we would expect α_{ph} to be proportional to T^3 over the entire measurement range.

Measurements of the thermal conductivity κ of the silicon wafers on which the metal-insulator-semiconductor structures were fabricated showed that, as usual in insulators, the heat is transferred by phonons, which are scattered by the boundaries of the sample. We found $\kappa \sim 10^{-2}\, T^3$ W/(K·cm) over the entire temperature range. The structural features on the $\alpha_{ph}(T)$ curve must therefore result exclusively from features of the phonon-electron interaction.

The phonon drag in a $2D$ system is given in order of magnitude by

$$\alpha_{ph} \sim \Gamma_{ph,e}\, W, \tag{1}$$

where W is the energy flux of the thermal phonons, and $\Gamma_{ph,e}$ is the damping of phonons due to their interaction with charge carriers. This interaction of the phonons can be singled out directly by examining the ratio $(\alpha\kappa^{-1})$, especially since this quantity can be determined experimentally within an error (3–5%) smaller than that possible for α or κ separately. We see in Fig. 2 that there is a clearly defined maximum on the curves of $(\alpha\kappa^{-1})$ for the n-type samples. The temperature corresponding to this maximum, T^*, depends on the electron density (Fig. 3) and behaves as if the anomaly always occurred at the same value of the ratio $q(T^*)K_F^{-1}$. The dashed curve in Fig. 3 shows $q(T^*) = 1.9K_F$ according to the results for three samples. We recall that in a $2D$ system the Fermi momentum is $K_F \sim N_s^{0.5}$. The inset in Fig. 3 shows the behavior of the relative change in the phonon-electron interaction for several values of N_s (the curve labels, in units of 10^{-12} cm^{-2}).

The structural features at $q(T) \simeq 2K_F$ is unusual in that the phonon-electron interaction intensitifies by a factor of several units there. As usual, the Kohn anomalies at $q \simeq 2K_F$ correspond to a change of only a few percent in the phonon dispersion curves.

The apparent reason for the greater magnitude of the observed effect is the two-dimensional nature of the system of charges with which the phonons interact. Hensel *et al.*[3] were apparently the first to assert that the Kohn features would be more clearly defined in $2D$ systems.

This assertion is supported by calculations of the acoustic absorption $\Gamma(q)$ carried out by I. M. Suslov. Calculations based on the results of Ref. 4 yielded the following results for $3D$ and $2D$ systems of charges:

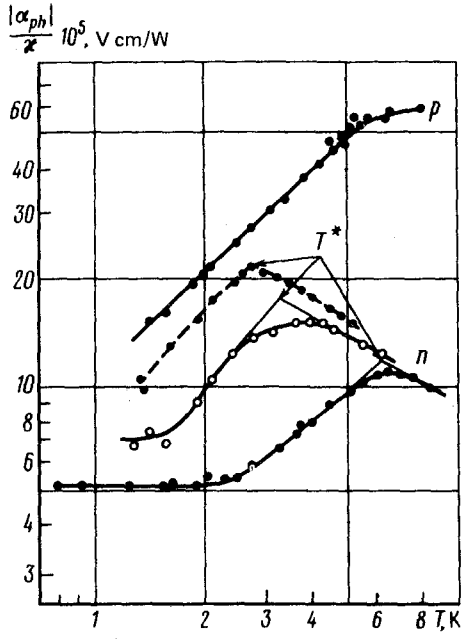

FIG. 2. Ratio of the phonon drag to the thermal conductivity of samples with the following densities N_s. For the n-type samples: Filled circles—4.5×10^{12} cm^{-2}; open circles—1.4×10^{12} cm^{-2}; dashed curve—0.7×10^{12} cm^{-2}. For the p-type samples: 4.1×10^{12} cm^{-2}. The straight lines are used in determining T^*.

$$\Gamma(q)_{3D} = \frac{m^{*2}\gamma^2}{2\pi\hbar^2\bar{u}\rho_{3D}}\, q\,\Theta(2K_F - q),$$

$$\Gamma(q)_{2D} = \frac{m^{*2}\gamma^2}{2\pi^2\hbar^2\bar{u}\rho_{2D}}\, q\,\frac{1}{\sqrt{2K_F - q}}\,\Theta(2K_F - q), \tag{2}$$

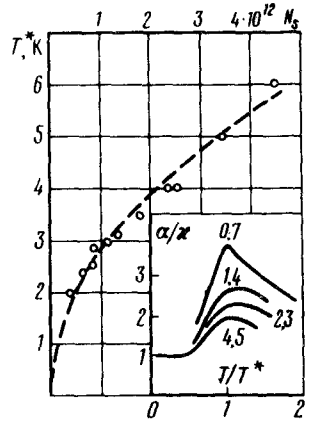

FIG. 3.

where γ is the strain energy, m^* is the effective mass of the charges, ρ is the density, $\bar{u}$ is the average sound velocity, and $\Theta(x) = 1$ at $x > 0$ and $\Theta(x) = 0$ at $x > 0$. If the phonon flux is not monochromatic (it was not in the present experiments), we must use in (1) a value $\Gamma_{\text{ph},e}$ averaged over the phonon distribution in the heat flux. The effect is to smooth out the structural features in $\Gamma(q)$ which follow from (2).

As mentioned previously,[2] the phonon-electron interaction changes as we go from the region with $q\Lambda \gg 1$ to the region with $q\Lambda \lesssim 1$. The change is seen in the temperature dependence $\alpha_{\text{ph}}(T)$ for the p-type structures (Figs. 1 and 2), for which the condition $q\Lambda = 1$ holds in the measurement interval because of the lower conductivity. In the temperature interval 1–4.5 K, we find $\alpha_{\text{ph}} \sim T^4$ for these samples and, correspondingly, $\alpha\kappa^{-1} \sim T$. At higher temperatures we see a tendency toward a transition to $\alpha_{\text{ph}} \sim T^3$, with $\alpha\kappa^{-1}$ constant. Weish to call attention to the fact that the thermal emf of the samples is much higher than for n-type samples. We believe that the difference stems from the difference in the effective masses of the electrons and holes[1] ($m_n^* = 0.19m_0$, $m_p^* = 0.55m_0$), since we have $\alpha \sim m^{*3} K_F^{-1}$ according to calculations[2] for the $2D$ case. The twofold degeneracy makes the electron Fermi momentum smaller than that of holes by a factor of $\sqrt{2}$.

The value of γ in (2) for an inversion channel can be found from the measurements of $\alpha\kappa^{-1}$ through the use of Eqs. (A4) and (A13a) of Ref. 2. For the n-type samples we use the measurements taken for $N_s = 4.5 \times 10^{12}$ cm^{-2} at $T < 2.5$ K, where $q < K_F$ and $\alpha\kappa^{-1} = 5$ V cm/W (an average value over three samples); for the p-type samples we use the results at $T > 4.5$ K, where $q\Lambda > 1$. Substituting these values into the corresponding expressions, we find $\gamma \simeq 8$ eV for both the n–type and p-type structures. This value of γ is much lower than that ($\gamma \gtrsim 17$ eV) which had to be adopted in several calculations[1] in order to explain the temperature dependence of the resistance of metal-insulator-semiconductor structures.

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