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Imaging of the Phonon-Drag Effect in GaAs-AlGaAs Heterostructures

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A channel of a two-dimensional electron gas in GaAs-AlGaAs heterostructures was irradiated with ballistic phonons at 1.2 K. No magnetic field was applied. A phonon-drag voltage was measured along the channel when phonons were absorbed in the channel and if the wave vector of these phonons had a component directed along the channel. The anisotropic nature of this phonon-drag effect was established with the phonon-imaging technique. From the comparison of the data with theory it follows that the electron-phonon coupling is of the piezoelectric type.

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The interaction of a two-dimensional electron gas (2DEG) with acoustic phonons has been studied by different techniques in recent years.[1-3] In those experiments either the scattering of the phonons,[1] the spectrum of the phonons emitted by a 2DEG,[2] or the heating of the 2DEG by phonon absorption was measured.[3] One of the most important observations was that only the component of the wave vector parallel to the 2DEG ($\mathbf{q}_{\parallel}$) is conserved during the interaction with a phonon. At low temperatures, there is the additional restriction that $\mathbf{q}_{\parallel}$ must be less than $2k_{\mathrm{F}}$ because of the Fermi statistics of the 2DEG.

In this Letter we introduce a novel experimental probe: the phonon-drag voltage which is caused by the incident ballistic-phonon flux. If a phonon is absorbed by the 2DEG, the $\mathbf{q}_{\parallel}$ component of the phonon wave vector is transferred first to one electron. Within a very short period of time, this momentum is distributed over all the electrons of the 2DEG by electron-electron scattering. The result is a collective momentum of the 2DEG equal to $\hbar\mathbf{q}_{\parallel}$ and a drift velocity $\mathbf{v}_D$. Thus a constant phonon flux impinging on the 2DEG will accelerate it until impurity and phonon scattering lead to a steady flow. If the $\hbar\dot{\mathbf{Q}}_{\parallel}$ is the rate at which phonon momentum is transferred to the 2DEG, then one expects $\mathbf{v}_D = \hbar\dot{\mathbf{Q}}_{\parallel}\tau/m^*$ as the steady-state velocity. Here m^* is the effective mass and τ is the momentum relaxation time which is also known to determine the electron mobility $\mu = e\tau/m^*$.

In an experimental situation one has a channel along, say, the x direction and a suitable voltmeter connected to it. In this case, no charge current can be set up by the phonon drag, but an opposing electric field builds up. Its value is given by $\mathbf{E} = -\hbar\dot{\mathbf{Q}}_{\parallel}/e$. The voltmeter measures the field component along the channel $V = -\hbar\dot{Q}_x l/e$, where l is the channel length.

This phonon-drag voltage is, of course, related to the phonon-drag contribution to the thermal voltage. In the case of the 2DEG in GaAs-AlGaAs heterostructures, this effect has received much attention recently.[4-7] There are two main differences in our approach. First, we do not have a temperature gradient along the 2DEG, and there is thus no thermal diffusion of the electrons. Second, we can control the angle of phonon incidence and, in principle at least, the phonon frequencies.

For the experiments we used GaAs-AlGaAs heterostructures prepared by molecular-beam epitaxy.[8] Nominally undoped wafers of 0.5 mm thickness and (001) orientation were used as substrates. On the front side, the 2DEG formed at the boundary between layers of GaAs (2 μm thick) and $\mathrm{Al_{0.35}Ga_{0.65}As}$ (67 nm thick). The AlGaAs was doped with Si except for a 19-nm-thick spacer layer, and was covered by a 10-nm GaAs protection layer. The 2DEG had a charge density of 6×10^{11} $\mathrm{cm^{-2}}$ and a mobility of 6×10^{5} $\mathrm{cm^2\,V^{-1}\,sec^{-1}}$, as measured at 1.2 K.

The experimental setup is shown in Fig. 1. A rectangular slab measuring 5×8 $\mathrm{mm^2}$ was cut out of the wafer. A 2DEG structure which consisted of two contact areas (0.5×0.8 $\mathrm{mm^2}$ each) was then etched out. These areas were connected by a 50-μm-wide and 80-

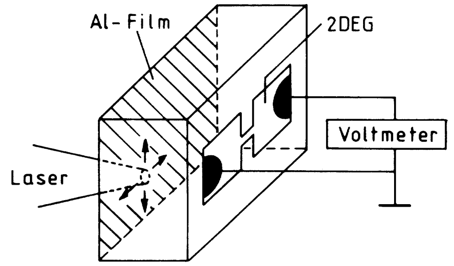

FIG. 1. Experimental setup (not to scale). The phonons are generated in the region of the laser focus. After propagating ballistically through the crystal, they set up a phonon-drag voltage along the constriction in the 2DEG.

μm-long bridge which later served as the active element. Electric contacts were made to the 2DEG by our diffusing In pellets at about 400 °C for 5 min. The far side of the slab was covered by a granular Al film of 200 nm thickness.

The sample was immersed in liquid He at 1.2 K. Phonons were generated by heating of the Al film with a laser focused onto a spot of less than 100 μm in diameter. We used either a cw HeNe laser (623-nm wavelength) or a diode laser (908 nm). Since the Al film was superconducting with a T_c near 2 K, the emitted phonon spectrum consisted mainly of frequencies around the gap frequency, which was 120 GHz in our film.[9] After being emitted, the phonons traveled ballistically through the GaAs substrate. Some of them impinged on the 2DEG and caused the phonon-drag voltage. This voltage could be measured either with a lock-in amplifier (for the chopped HeNe laser) or a boxcar amplifier (for the pulsed diode laser). In the course of an experiment, the locus of the phonon generation, i.e. the laser-heated spot, is raster scanned across the Al film under computer control.[10] Thus the small bridge in the 2DEG is irradiated by phonons from varying directions. Simultaneously, the phonon-drag voltage is recorded as function of the laser coordinates.

In an experiment of this kind, the phonon flux will be strongly modulated by phonon focusing. Because of the anisotropy of the GaAs crystal structure, the phonons are "bunched" into certain directions.[10] The phonon-focusing effect can only be observed, however, if the phonons propagate ballistically and if the experiment has sufficient spatial resolution to resolve the very sharp phonon-focusing structures.

The expected phonon-focusing distribution can easily be calculated from acoustic theory.[10] This was done for GaAs with a Monte Carlo technique. The result is shown in Fig. 2(a) as a grey-tone image. Bright areas denote regions from where a high phonon-flux intensity will be impinging onto the 2DEG bridge if they are laser heated. The highest intensity is expected in the center where the phonons propagate near the [001] direction, almost perpendicular to the substrate surface. Sharp ridges extend along the {100} planes and less pronounced ones along the {110} planes. These ridges stem from fast transverse phonons (FTA) and slow transverse phonons (STA), respectively. The strong maximum at the center is a mixture of the two phonon modes. The longitudinal phonons (LA) are only weakly focused and are almost invisible in this representation.

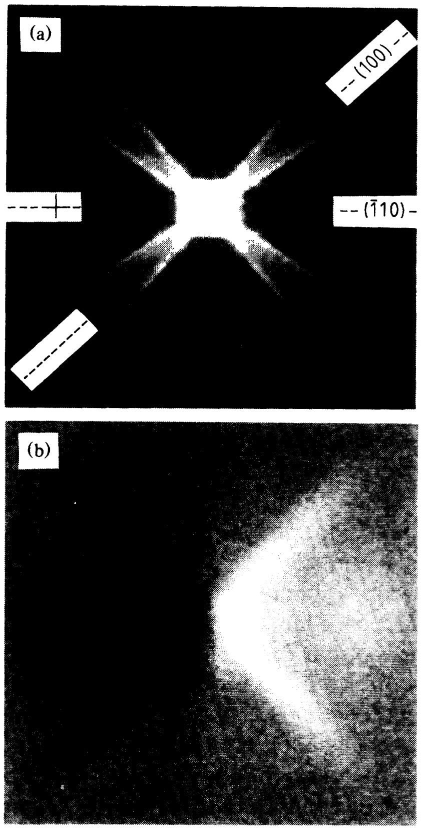

FIG. 2. (a) Calculated phonon-focusing pattern in GaAs. The bright square in the center is due to transversely polarized phonons propagating near the [001] direction. The sharp ridges along the {100} and the {110} planes are caused by the focusing of fast and slow transverse modes, respectively. Two of these planes are marked in the figure. The cross on the left-hand side, on the ($\bar{1}$10) plane, marks the [$\bar{1}\bar{1}$1] direction. (b) Measured phonon-drag voltage pattern. Bright and dark areas correspond to positive and negative voltages, respectively. The length scale of this image was scaled to the one of (a) within an experimental uncertainty of about 10%. The fast-transverse-mode ridges are clearly visible. The two broad and relatively weak structures off the central square, a maximum and a minimum, are due to longitudinal phonons propagating along the [111] and [$\bar{1}\bar{1}$1] directions. The LA phonons are too weakly focused to be visible in (a).

The measured phonon-drag voltages are presented in Fig. 2(b). Zero voltage corresponds to an average grey tone while positive and negative values are displayed brighter and darker, respectively. This measurement was made with an estimated absorbed laser power of 20 μW. The maximum measured voltage was about 0.5 μV. Clearly, several sharp features are visible which indeed coincide with some of those of the focusing pattern. Most prominent are the ridges which extend along the {100} planes. Striking is the reversal of the voltage sign whenever the q_x component of the incident phonon flux reverses its sign. This is exactly what is expected if the phonons drag the electrons toward either one or the other contact. Equally striking is the fact that some of the focusing structures, for example, the STA modes along the {110} planes, do not show up in the phonon-drag pattern. The two broad structures along the ($\bar{1}\bar{1}$0) planes are due to LA phonons as revealed by time-resolved measurements. The centers of these structures are, within experimental uncertainty, the $[111]$ and $[\bar{1}\bar{1}1]$ directions, respectively. It is noteworthy that we obtained the same phonon-drag pattern by using 100-nsec laser pulses and a boxcar gate time of about 300 nsec instead of a cw laser and the lock-in amplifier.

The sharpness of the structures in the phonon-drag pattern is proof that only the small bridge between the two contacts is the active area of the 2DEG. Of course, phonon drag also induces electric fields in the contact areas, but these areas are relatively large and the focusing patterns are completely smeared out. For the same reason it can be ruled out that we observed a thermal voltage of any kind. To explain the sharp structures one would need a contact between *different* materials at exactly the position where the 2DEG bridge connects to the contact areas made out of the *same* 2DEG material.

The absence of the STA phonons in the data is an indication that the phonons of different modes couple differently to the 2DEG. In a polar solid like GaAs there are two possible types of electron-phonon coupling: deformation potential and piezoelectric. The first one seems to be favored in the literature for calculations of electron mobilities at low temperatures.[11] On the other hand, the predominance of piezoelectric coupling was concluded from phonon emission from (3D) GaAs epilayers.[12] In the case of deformation-potential coupling, the square of the matrix element M for absorption of a phonon with wavevector $\mathbf{q}$ by electrons is proportional to $(\mathbf{q}\cdot\mathbf{a})^2$, where $\mathbf{a}$ is the polarization vector of the phonon. The corresponding expression for piezoelectric coupling is proportional to $(a_x q_y q_z + a_y q_z q_x + a_z q_x q_y)^2$.[13] Thus the electron-phonon interaction is anisotropic in both cases and the anisotropy differs for the two types of interactions. This difference offers a unique opportunity to determine which type of interaction is relevant for the 2DEG in GaAs.

Therefore, we redid the calculation of Fig. 2(a) but multiplied the respective phonon intensities by a calculated $\dot{Q}_x$. The value of $\dot{Q}_x$ was obtained from

$$\dot{Q}_x = \int q_x [\Gamma(\mathbf{q})/v] F(\mathbf{q})\, d\mathbf{q}\,,$$

where $\Gamma(\mathbf{q})$ is the absorption probability of the phonon, v is the sound velocity, and $F(\mathbf{q})$ is the intensity spectrum of the incident phonon flux. From Fermi's "golden rule," one gets

$$\Gamma(\mathbf{q}) = \frac{2\pi}{\hbar} \sum_{\mathbf{k}_i} |M|^2 \delta(\epsilon_i + \hbar\omega - \epsilon_f) f(\mathbf{k}_i)[1 - f(\mathbf{k}_f)]\,,$$

where M is the matrix element and the initials i and f denote the initial and final $\mathbf{k}$ states of the electrons with energy ϵ and occupation number $f(\mathbf{k})$, respectively. Phonon emission was neglected. The evaluation of $\Gamma(\mathbf{q})$ was similar to the one by Rothenfusser, Köster, and Dietsche.[2] The phonon frequency was assumed to be 120 GHz, the dominant phonon frequency of superconducting Al.

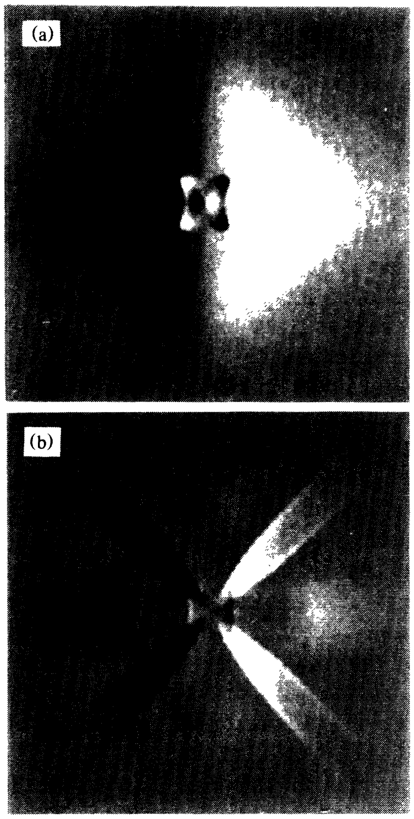

FIG. 3. Theoretical phonon-drag patterns with the assumption of (a) deformation-potential coupling and (b) piezoelectric coupling. Only the latter image coincides with the experimental data.

The resulting theoretical patterns of the phonon-drag voltage are depicted in Figs. 3(a) and 3(b) for deformation potential and piezoelectric couplings, respectively. The units of the voltage values were arbitrary in both cases. Clearly, the two patterns differ significantly from each other. It is quite apparent that the piezoelectric pattern agrees better with the experimental data because (i) it clearly shows the FTA ridges along the $\{100\}$ planes rather strongly, while these are absent in the deformation-potential coupling pattern; and (ii) it reproduces the shape of the observed LA pattern better. The STA ridges which were missing in the experimental data are not visible in either case. Thus, we conclude that the phonon absorption in our experiment is dominated by piezoelectric scattering.

In summary, we have shown that the absorption of ballistic phonons leads to a measurable phonon-drag voltage in GaAs-AlGaAs heterostructures. To our knowledge, this is the first demonstration of this kind in the field of ballistic-phonon physics. Using the phonon-imaging technique, we found that the phonon-drag voltages depend on the absorption strength of the respective phonon modes. Comparison with theoretical phonon-drag images revealed that piezoelectric electron-phonon interaction is the relevant coupling process.

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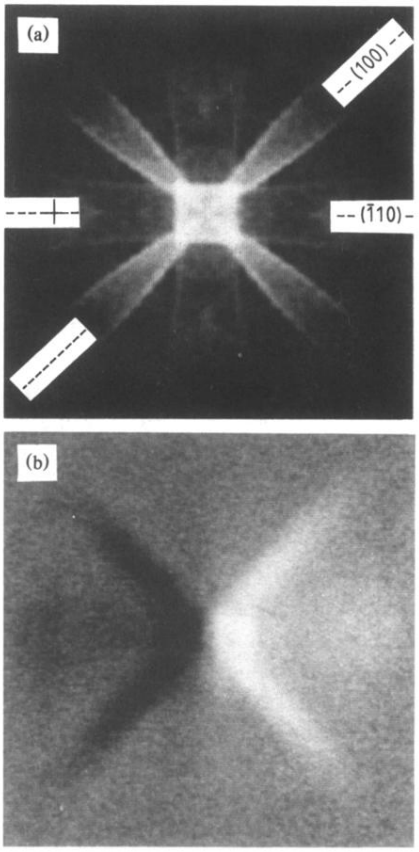

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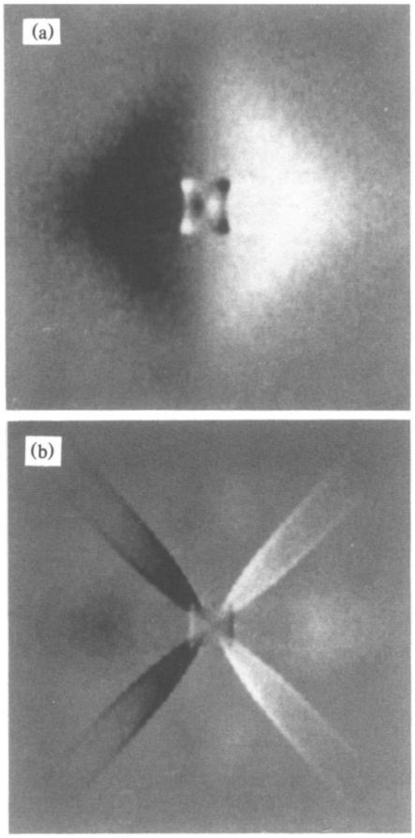

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