New Phenomena in Coupled Transport between 2D and 3D Electron-Gas Layers

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(Received 27 July 1989)

We report, for the first time, measurements of a current-to-current coupling between 2D and 3D electron-gas (EG) layers in the AlGaAs/GaAs system, utilizing an n^+ GaAs gate as the 3DEG layer. Current driven through either of the layers, which are only 30 nm apart, induces current flow in the other layer. Current-to-current transfer ratios of the order of 3×10^{-5} have been observed, and there is a sign reversal of the interaction at temperatures below 40 K. This and other effects can be explained by invoking Coulomb mutual scattering to couple energy and momentum between the two layers.

PACS numbers: 73.50.Dn

With the advent of atomic-layer control in molecular-beam-epitaxy–fabricated heterostructures between GaAs and (Al,Ga)As, it has been possible to devise structures and do experiments which previously were only discussed in theory. One such experiment is the study of coupled transport between independently contacted two-dimensional electron-gas (2DEG) layers situated only tens of nm apart, where a transfer of momentum due to the Coulomb mutual scattering (CMS) effect[1] should be observed. In this Letter we report on such an experiment, although in the present work we have closely spaced 2DEG and 3DEG layers rather than a pair of 2DEG layers. Our results are explicable in terms of the CMS effect, although its manifestation in our samples is rather complex, being predominantly[2] due to momentum transfer at high temperatures and energy transfer at lower temperatures. Our experiment is reminiscent of the landmark one by Hubner and Shockley[3] (where phonon transfer was detected), except that our distance scale is 1000× smaller.

We apply a technology previously used for field-effect transistors[4] (FET's) where a GaAs gate is separated from the channel by an $Al_{0.5}Ga_{0.5}As$ barrier. A positive gate voltage induces a 2DEG in the channel which is contacted via self-aligned ion-implanted contacts. The high-temperature anneal (900 °C) necessary to activate the ion implant does not affect the quality of the heterostructure, to first order, in terms of capacitance versus voltage characteristics, gate leakage currents, or channel mobility.[5] In this Letter we will present a summary of the results obtained in such structures, with a detailed account to be given in a future publication.

The sample's structure is shown in Fig. 1(a), and a typical measurement circuit in Fig. 1(b). The sample is on a (001) surface with current flow perpendicular to a ⟨011⟩ axis. Because of the smallness of the coupling and the possibility of spurious coupling effects, stringent experimental precautions were necessary. Lock-in techniques are used, at a frequency of 105 Hz. The applied signal voltage is much smaller than the gate bias so that the FET is operating in a linear regime, typically 10 mV rms, versus about 0.5 V dc for the gate bias. The measurement is done under short-circuit conditions since the impedances of both source and detector are less than the sample input or output impedance. The measurement is close to dc, i.e., it is frequency independent, with no device-induced phase shift, ensuring negligible capacitive or inductive coupling. Induced piezoelectric or other effects not involving a transfer of power between the gate and channel circuits are not detected because the dielectric relaxation times in the gate and channel are much shorter than the measurement time. A metal-film capacitor in series with the detector measurement circuit blocks dc current, such as could be caused by an external thermal emf, which would otherwise result in spurious coupling due to normal FET modulation of carrier density. The insulating quality of the AlGaAs barrier is sufficient to limit gate leakage current to $<1\times10^{-5}$ of the source-drain current over a 0.2-V range in gate voltage above threshold. The circuit configuration in Fig. 1(b) further improves the discrimination by canceling

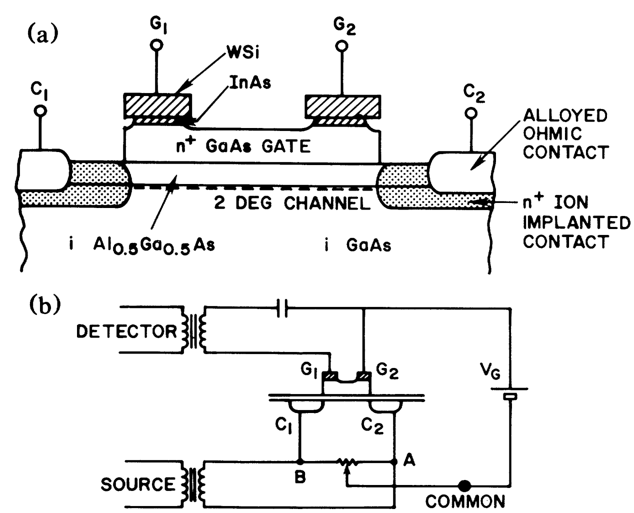

FIG. 1. (a) Device structure showing the ion-implanted contact to the channel and WSi/InAs contact to the gate. (b) Measurement circuit showing method for compensating for leakage.

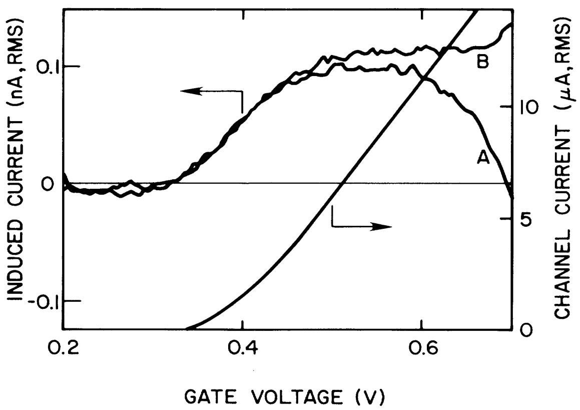

FIG. 2. Current induced in the gate, and ac channel current, as a function of gate bias, at 80 K, with a voltage of 6.7 mV rms applied to the channel. For curves labeled *A* and *B*, the common is at nodes *A* and *B* in Fig. 1(b).

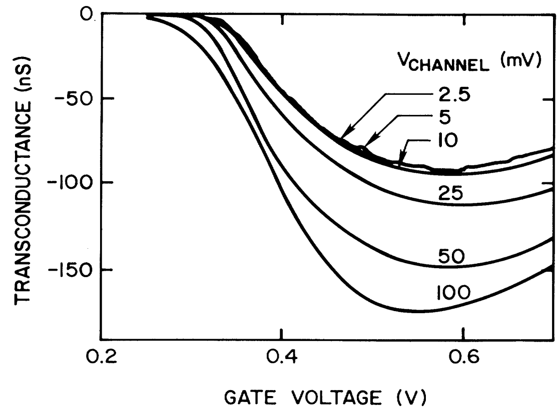

FIG. 3. Transconductance [(induced gate current)/(channel voltage)] vs gate bias at 30 K. Channel voltage is the parameter. Leakage current has been compensated for.

out the average contribution of the leakage current when integrated over the channel. It can be appreciated that by changing the position of the circuit ground from *A* to *B* the contribution of the leakage current to the coupling can be made to change sign, whereas a "transformerlike" coupling (which contains the physics we are interested in) is unaffected. The arrangement of Fig. 1(b) can be inverted, the signal being applied to the gate and detected on the channel.

The experiments were performed on several wafers having similar characteristics (determined by the requirements of the FET technology) with AlGaAs thicknesses of about 30 nm and an AlAs mole fraction of 50%. The doping in the gate was about 2×10^{18} cm^{-3} (*n* type) and the gate thickness, after chemical etching, was 50–100 nm. Mobilities of the 2DEG at 80 K ranged from 1×10^5 to 2×10^5 cm^2/Vs. Device sizes ranged from 70×40 to 8×6 μm^2, the first dimension being in the direction of current flow. Devices with both two and four gate contacts, spaced roughly equally in a line, were used. A special set of back-to-back devices, sharing a common axis of current flow and having an interdevice separation of 10 μm, was used to test for lateral coupling effects.

The experimental results will be discussed in terms of two temperature ranges centering about 80 to 30 K, for reasons which will become obvious. Results for different wafers and for different devices on the same wafer were qualitatively similar. The results are displayed as a transconductance, since its magnitude is unaffected by the parallel conductance of any of the 3DEG gate electrons not contributing to the coupling.

Measurements at 80 K of the coupled signal in the gate, as well as the ac channel current, are shown in Fig. 2 as a function of gate bias. It is seen that the coupled signal "turns on" at the same gate bias as the FET, yet while the channel current continues to increase, the coupled signal saturates, and indeed may even decrease in some devices. The influence of the leakage current, which increased quasiexponentially with gate bias, is small below 0.6 V, as verified by changing the position of the ac ground (from *A* to *B* in the figure). The direction of the signal is consistent with a simple transfer of momentum between electrons in the channel and in the gate. The coupled signal is linear with the applied ac voltage, up to 100 mV rms, except for normal debiasing effects. Tellegen's reciprocity theorem for linear networks is obeyed in that the transconductance is the same, at the same bias, when gate and channel terminals are interchanged. For multiple gate contacts the magnitude of the current is independent of the pair of contacts chosen, to within 20%. The effect is reproducible from device to device on the same wafer.

At 30 K the results are much different, as is seen in Fig. 3. Although similarly turning on with the FET channel current, and being uninfluenced by gate leakage current, the coupling coefficient has changed sign. The output is linear up to an applied ac voltage of only 10 mV when applied to the channel and only $\simeq 2$ mV when applied to the gate, after which it becomes superlinear. The magnitude of the effect varies considerably from sample to sample and is not seen equally at all contacts, being weakest between the middle contacts. The temperature dependence of the transconductance, for a typical sample, is summarized in Fig. 4, which also shows the extent of the reciprocity of the effect.

In trying to explain these results, we consider mechanisms involving transmitted phonon drag,[3] thermoelectric effects,[6] and the CMS[1,7] effect. Of these the thermoelectric effect alone can obviously account for the sign of the coupling at low temperatures, as well as giving a peak in the right temperature range,[8] where it is

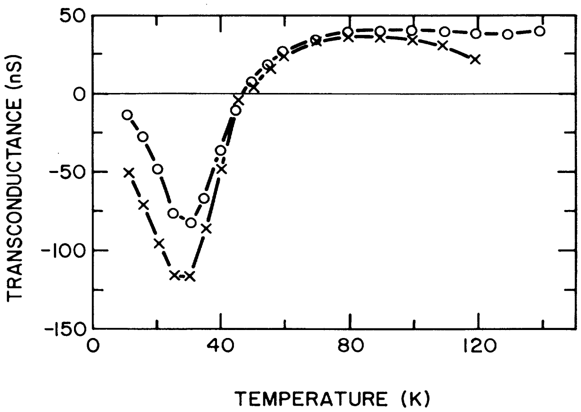

FIG. 4. Temperature dependence of coupled signal when driving voltage is applied to the channel (O) or to the gate (×).

enhanced by phonon drag. The current in the channel generates a temperature difference between the end contacts via the Peltier effect, which is detected at the gate contacts as a thermal emf. However, there are strong arguments against this explanation. For the back-to-back devices, the gate contacts of the second device were used as a thermocouple, to detect any signal caused by current flowing between the channel or gate contacts of the first. The observed coupling strength was about 5000× smaller than that within the same device. Thermal calculations based on the spreading geometrical configuration of the devices indicate that the ratio should be more like 10:1. This argues that the coupling cannot be thermal in origin. Theoretical considerations give the same conclusion. The thermoelectric transimpedance, Z_{21}, may be expressed as

$$Z_{21} = \alpha S_1 S_2 T/\kappa w\,, \tag{1}$$

where S_1 and S_2 are the thermoelectric powers of the gate and channel, respectively, κ is the thermal conductivity of the substrate, w is the width of the device perpendicular to the direction of current flow, and α ($\simeq 1$) is a geometrical factor taking thermal spreading effects into account. Assuming S_1 and S_2 to be diffusive electronic thermopowers according to standard formulas,[9,10] for the 2DEG channel and the 3DEG gate, respectively, gives a coupling strength $\simeq 1000\times$ smaller than that measured. Assuming that the thermopower is enhanced by phonon drag does not help. First, the phonon-drag thermopower for our small devices should vary as the square of the ratio of the device length ($\simeq 20$ μm) to the mean free path for acoustic phonons in the substrate.[11] For the long-wavelength phonons which interact with electrons the latter is $\simeq 1$ mm.[12] Furthermore, were phonon drag dominant, the direct Hubner-Shockley (HS) effect would be much larger than the indirect thermoelectric component at these temperatures; hence the net effect would be of normal sign. One reason for this is the above geometrical factor which greatly reduces the thermoelectric coupling but does not reduce the HS effect. Another reason is that the returning, thermalized phonons occupy a much larger volume of phase space (and thus are diluted) compared with the phonons involved in the HS effect which have subthermal wave vectors of less than $\min(2k_{F1}, 2k_{F2})$, where k_{F1}, k_{F2} are the Fermi wave vectors of the two electron-gas layers. Another mechanism which might have given the sign reversal is the reflection of phonons from the channel to the gate via the ends of the device. The back-to-back samples were designed to test for this possibility, where the downstream device would have intercepted the phonons generated by the upstream one. But, as we mentioned, this gave a null result.

Remote electron-electron scattering (CMS effect) has been worked out for the case of two 2DEG layers.[1] Boiko and Sirenko[13] have analyzed the case of 2DEG-to-3DEG coupling. Jacoboni and Price[7] simulated a 3DEG-3DEG case using a Monte Carlo method, calculating energy transfer for hot electrons rather than momentum transfer among essentially thermal electrons. The above cases are not applicable to our situation because only nondegenerate electrons were considered in detail. Recently, Laikhtman and Solomon[2] have worked out the theory of the Coulomb coupling under conditions similar to those in our experiment and found that the major features of our results, as presented above, can be explained by the CMS effect. A qualitative description of the mechanism will be presented below while the details will be submitted in a separate publication. Two CMS effects compete: direct momentum transfer and energy transfer, which result in couplings of opposite signs. At high temperatures the direct coupling via momentum transfer dominates. This effect was shown[2] to saturate with gate voltage and with temperature above $\simeq 80$ K, in agreement with experiment. The negative contribution involves a generation of Peltier heat at the contacts, and hence a heating/cooling of the electrons in the channel near the contacts and the subsequent CMS transferal of this heat to the electrons in the gate. This explanation is analogous to the one which we rejected which invoked a thermoelectric effect except that temperatures are now electron temperatures, with a negligible change in lattice temperature, and the Peltier effect and heat transfer are entirely electronic. The negative effect is dominant at the lower temperatures because the Bloch-Gruneisen effect causes the thermalization, via acoustic phonons, to be strongly reduced with decreasing temperature ($\propto T^4$),[2] allowing for local differences in electron temperature even at the low values of electric field used in the experiment. The superlinear behavior with channel voltage is not yet explained in an entirely satisfactory manner, although an appreciable rise in the electron temperature in the channel above ambient should increase the magnitude of the negative coupling. While most of the experimental observations are qualitatively explained by this new theory, the magnitude predicted for both coupling mechanisms is about an order of magnitude too large. Idealizations and approximations in the theory may account for this discrepancy.

In summary, we have investigated the transconductance for close parallel electron-gas layers and have seen anomalous sign reversal and nonlinear effects. The coupling is shown to be short range, i.e., within the device. Conventional explanations involving phonon-electron thermopower do not work. An explanation by Laikhtman and Solomon[2] appears to explain most of the pertinent facts. Coupling is via CMS without appreciable involvement of phonons. The reversal of sign is explained by a thermoelectric effect, but involving electrons only, not the lattice system. We conclude therefore that we have observed both momentum and energy transfer between closely coupled 2DEG and 3DEG layers via the CMS effect.

We wish to thank B. Parker for the use of his electrical measurement system, B. Laikhtman for allowing us to use his as yet unpublished theory, and A. Palevski and U. Sivan for useful discussions.

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