Frictional Drag Between Coupled 2D Hole Gases in GaAs/AlGaAs Heterostructures

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Abstract

We report on the first measurements of the drag effect between coupled 2D-hole gases. We investigate the coupling by changing the carrier densities in the quantum wells, the widths of the barriers between the gases and the perpendicular magnetic field. From the data we are able to attribute the frictional drag to phonon coupling, because the non-parabolicity allows to tune the Fermi wavevector and the Fermi velocity separately and, thereby, to distinguish between phonon- and plasmon-dominated coupling.

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The coupling mechanisms between two closely spaced two dimensional (2d) charge systems in semiconductors have found much interest recently. Even if tunneling between the layers can be neglected, the layers are coupled by the electron-electron interactions which leads to a transfer of momenta and a frictional drag between them. The drag force can be measured by passing a drive current $I_{\text{drive}}$ through one layer and measuring the resulting voltage drop $V_{\text{drag}}$ in the other one \[1\]. The coupling strength is usually stated as the transresistivity $\rho_T = (W/L)(V_{\text{drag}}/I_{\text{drive}})$ where $(W/L)$ is the width to length ratio of the sample. The transresistivity has been derived theoretically based on RPA and is found to depend on the imaginary parts of the susceptibilities of the two layers $\chi_1, \chi_2$, on the interlayer interaction $V_{12}$ and on the dielectric constant $\epsilon_{12}$ of the combined system \[2,3\]:

$$\rho_T \propto \int_0^\infty dq q^3 \int \frac{d\omega}{2\pi} |V_{12}(q,\omega)|^2 \frac{\text{Im}\chi_1(q,\omega)\text{Im}\chi_2(q,\omega)}{\text{sinh}^2(\hbar\omega/2k_BT)}, \quad (1)$$

Two-dimensional electron gases (2DEGs) in GaAs/AlGaAs heterostructures in zero magnetic field have been found to couple via Coulomb interaction \[3\], via the excitation of coupled plasmons \[4\], and via the exchange of phonons with $q \approx 2k_F$ \[5\]. At zero magnetic fields the Coulomb coupling is weak compared to the other two mechanisms. At temperatures exceeding about $0.2T_F$ coupled plasmon modes are excited. This is most efficient if the Fermi velocities $v_F$ of the two layers coincide. The phonon coupling, on the other hand, is maximum if the $k_F$ values in the two layers are identical. Very recently, it has been suggested that coupled electron-phonon modes may exist under certain conditions leading to a vanishing of $\epsilon_{12}$ around $q = 2k_F$ \[6\]. No evidence for the existence of these coupled modes has been reported yet.

No experimental work has been published on the frictional drag between two 2d hole gases (2DHGs) and only preliminary data exist on mixed (2DEG/2DHG) systems \[2,7\]. In these systems the phonon coupling should be larger because of the larger effective hole masses. On the other hand $T_F$ is also smaller for the same reason and it is not clear if phonon or plasmon coupling should be expected to dominate at low temperatures. However, hole systems offer a unique possibility to discriminate between the different mechanisms because their energy
dispersion curves are nonparabolic and, moreover, this nonparabolicity can be tuned by varying the shape of the quantum wells by external fields or by doping. Therefore, these systems offer the possibility to tune both $k_F$ and $v_F$ and to achieve coincidences of either of these quantities at different densities in the two layers. The study of the drag between electron and hole gases will furthermore give information about the (in)congruences of the Fermi surfaces which limits the possibility to observe superfluidity in coupled 2DEG/2DHG systems by the reduction of the phase space for Cooper-pair-like scattering.

In this Letter we report the first, to our knowledge, measurements of the frictional drag between two 2DHGs as well as more detailed results on coupled 2DEG/2DHG systems. In both cases, the frictional drag is measured as function of the charge densities in the two layers. We also present data on samples having widely varying barrier thicknesses and we will discuss the effect of temperature and of magnetic field. We find a very asymmetric behavior with respect to the densities which is in contrast to the previously studied purely electronic systems, and we present evidence that the coupling is well described by phonon exchange and not by plasmon interaction.

The coupled 2DHG samples are prepared in two 20 nm thick quantum wells in GaAs/AlGaAs heterostructures. Remote doping was achieved using carbon with a spacer layer thickness of typically 20 nm. Six samples are produced with GaAs quantum wells separated by Al$_3$Ga$_{7}$As barriers with thicknesses varying from 30 to 190 nm. In some samples the doping of one well is placed inside the barrier leading to a strong asymmetry between the layers. The samples are shaped as a Hall bar geometry with 80 μm width and 800 μm length. Ohmic contacts to both layers are made by diffusion of Au and Zn. Separate contacts to the two layers are achieved by using the standard selective depletion technique. In this case, metallic front gates and p-doped buried backgates are used. Two more gates cover the main part of the Hall bar and allow the independent variation of the carrier densities. Typical hole mobilities at 4 K are between 40.000 cm$^2$/Vs and 80.000 cm$^2$/Vs which are reasonably good values for hole gases on (001) surfaces. The hole concentration can be varied typically from zero to about 5.10$^{11}$ cm$^{-2}$. Details of the coupled 2DHG/2DEG system are already
described in [7]. In this case the distance between the two layers is 340 nm.

The drag measurements are done by passing drive currents of 100 nA at a frequency of about 1 Hz through one of the layers and using lock-in technique to measure the resulting drag voltage in the other layer. The integrity of the signal is first controlled by checking that all leakage currents are unmeasurably small and cannot influence the signal. Second, the linearity between drag voltage and drive current value is confirmed, and third, the drag and drive layers are interchanged and the signals are found to be identical. Measurements are done in a standard cryostat at temperatures between 1.5 and 10 K and in magnetic fields up to 11 T.

First, we present data on the dependence of the transresistivity $\rho_T$ on the hole concentrations. The respective densities are determined by Shubnikov-deHaas measurements at 1.5 K. In Fig. 1 we show $\rho_T$ as a combined grey tone - contour plot at 2.8 K as a function of the upper and lower hole densities for a coupled 2DHG sample with $d = 140$ nm. In comparison to coupled 2DEG structures we find a rather complicated dependence of $\rho_T$ on the densities in the two layers. Particularly remarkable is the fact that there is no symmetry in the data if the two densities $p_{\text{upper}}$ and $p_{\text{lower}}$ are interchanged. At small densities in both layers ($\leq 3 \cdot 10^{11} \text{cm}^{-2}$) the maximal coupling strength is found along a ”ridge” (marked by heavy dots) running just below the condition of equal densities in the two layers. At higher densities, however, this ridge splits into two ones which run nearly vertically and horizontally in the figure (also marked by dots). This asymmetry with respect to the densities in the two layers must be consequence of the asymmetric doping of the two wells, because it is also seen in the other asymmetrically doped samples but not in the symmetrically doped ones where we find a very broad maximum of the coupling centered around the line of equal densities.

The asymmetric doping leads to an effective electric field in the respective quantum wells which causes the splitting of the highest hole subband into two. This effect has recently been studied in detail in just one hole layer [8]. The splitting of the subbands automatically leads to different values of $k_F$ and $v_F$ in the two bands, and $v_F$ is no longer proportional to $k_F^2$.
because of the strong nonparabolicity of the dispersion curves. Both quantities are available from the dispersion curves which we calculate in a self-consistent Hartree approximation based on a $4 \times 4 k \ast p$-method. Examples are shown in Fig. 2 (a) and (b). The $k_F$ of one branch is identical for the two layers even if their densities are out of balance. The loci of identical $k_F$ and of identical $v_F$ are plotted in Fig. 2 (c) and (d), respectively. The cross marks the case of Fig. 2 (a) and (b). Here we use the values obtained for the [110] direction in the plane. In the plots of (c) and (d) the solid lines correspond to the case where hole subbands with the same quantum number are coupled while the dashed lines indicates coupling between bands with different quantum numbers. A second line of this type lies far outside of the plot range.

Comparison of these plots with the data of Fig. 1 shows that only the phonon coupling between hole bands with identical quantum numbers agrees with the experimental data. In Fig. 1 the calculated locus of equal $k_F$ values in the equivalent bands is indicated as a solid line. If a similar analysis is made for the [100]-direction, one finds that the loci for coinciding $k_F$ respectively $v_F$ values do not differ significantly from those shown in Fig. 1 and Fig. 2. We conclude that the phonon exchange is the main source of coupling between the hole layers. The fact that only identical branches of the hole dispersion curves couple with each other is most likely due to the acoustical anisotropy of the GaAs which cause that only certain phonon modes (e.g. longitudinal or transversely polarised ones) couple to either one branch of the dispersion curves [10].

Similar experimental data have been obtained in a coupled 2DEG/2DHG system with a barrier of 340 nm. The transresistance as function of hole and electron concentration is shown in Fig. 3. These data are obtained at 5 K. Similarly to the case of coupled hole gases one finds an asymmetric behavior with respect to the two densities, particularly at large densities. We calculate again the $k_F$ and $v_F$ values of this 2DHG layers and compare them with $k_{F,e} = \sqrt{2\pi n}$ and $v_{F,e} = \hbar k_{F,e}/m^*$ of the 2DEG. The only satisfactory match with the experimental data is obtained using phonon coupling (i.e. matching the $k_F$ values) between the electrons and only one (the one with the heavier hole mass) of the hole branches. The
resulting locus of equal $k_F$ values is plotted in Fig.3 as the heavy line. In this case an angular average of the $k_F$ values of the hole gas is used. An interesting result of Fig.3 is that an approximate congruence as it is realised along the ridge of maximum coupling between the hole and the electron Fermi surfaces requires in general quite unequal densities between the two gases. In contrast to the case of coupled 2d hole gases, the ridge positions of the coupled 2DEG/2DHG system shifts significantly with increasing temperature because the phase space for scattering processes changes very differently for the electrons and the holes, respectively [7].

The coupling between two 2d charge gases depends on the distance between the two layers. Theoretical studies of the interaction via plasmons predict a strong decrease of the transresistivity with distance $\rho_T \propto d_{eff}^{-3}$ [4]. Here $d_{eff}$ is the distance between the center of gravity of the wave functions of the respective charge layers. On the other hand, the theory based on the exchange of coupled phonons predicts a logarithmic decrease with distance [6]. In Fig. 4 we show data of $\rho_T/T^2$ for six coupled 2DHG systems for two different temperatures as function of $d_{eff}$ at matched densities of $3 \cdot 10^{11} cm^{-2}$. There is some scatter in the data which is probably due to different preparation conditions of the samples which were fabricated over a time span of more than one year. Nevertheless, the comparison of the data with the two predicted thickness dependences shows clearly that the logarithmic dependence is a better description of the data. A fit using $\rho_T/T^2 \propto ln(l_{ph}/d_{eff})$ with $l_{ph}$ being the mean free path of the phonons, as suggested in [6] for the case of damped phonons, gives $l_{ph} \approx 300 nm$. This number is small compared to the mean free paths deduced from thermal conductivity or heat pulse data for high quality GaAs but agrees quite well with the typical length scale of inhomogeneities along MBE grown layers as observed by AFM studies [11].

Finally we investigate the dependence of the transresistivity on perpendicular magnetic fields. In earlier studies in 2DEG/2DEG systems a dramatic increase of $\rho_T$ was observed except right under the quantum Hall effect conditions where $\rho_T$ vanishes [12]. A less dramatic increase was seen in the 2DHG/2DEG systems [13]. The 2DHG/2DHG systems are different
because quantisation effects are small in most of our magnetic field and temperature regimes. Experimental data are shown in Fig. 5 where $\rho_T$ is plotted as function of a perpendicular magnetic field. The barrier thickness is 40 nm, the carrier-density is $2.5 \cdot 10^{11} \text{cm}^{-2}$ in both wells. At the lowest temperature $T=1.5 \text{ K}$, $\rho_T$ reflects the Shubnikov-de-Haas-oscillations of $\rho_{xx}$ but the increase of the maxima with field is less than with the previously studied systems involving electrons [12,13]. At higher temperatures these quantisation effects disappear, but now $\rho_T$ shows a decrease with increasing magnetic field. At even higher temperatures the $\rho_T$ seems to become nearly independent of the magnetic field. Interestingly, this behavior is just the opposite to the one of $\rho_{xx}$ which increases with magnetic field in the same experimental range. The general decrease of $\rho_T$ at intermediate temperatures and its flattening at higher temperatures is also observed with densities which were not matched between the two layers and with samples having wider barriers. This behavior can be qualitatively understood from the behavior of the susceptibility $\text{Im} \chi(q, \omega)$ at $q \simeq 2k_F$ in magnetic fields. At zero magnetic fields this function has a strong maximum near $q \simeq 2k_F$ on which most of the analysis of this paper is based. This maximum disappears with magnetic field as was shown theoretically by Glasser [14]. Thus, the coupling via phonons with $q \simeq 2k_F$ is weakened in magnetic field.

At quantising fields which correspond to the usual situation in systems involving electrons, this argument is no longer applicable because other types of interactions are dominant [13].

In conclusion we report the first data of the frictional drag between coupled 2d hole gases. By variation of doping profiles and the application of gate voltages we vary $k_F$ and $v_F$ independently from each other and establish that the coupling mechanism is dominated by phonon coupling at wavevectors $\simeq 2k_F$. The coupling between 2d electron and 2d hole gases can be described within the same model. We find a logarithmic dependence of the coupling on the distance between the layers which agrees with a theoretical prediction of coupled phonon-plasmon modes. For the coupled hole gases we find a decrease with magnetic field as long as we are in the classical regime, which is consistent with the expected behavior of the susceptibilities at large wave vectors.

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FIGURES

FIG. 1. Contour plot of the transresistivity as function of the carrier-densities in the upper ($p_{upper}$) and the lower ($p_{lower}$) 2DHG at $T=2.8$ K. The barrier-thickness is 140 nm. White areas indicate the strongest ($550 \, m\Omega\square$), the black ones ($230 \, m\Omega\square$) the weakest coupling. The dotted lines run along the "ridges" of maximal $\rho_T$. The heavy lines show the locus of coinciding $k_F$ values in equivalent subbands in the two layers.

FIG. 2. Dispersion curves of the lower (a) and the upper (b) 2DHG which can correspond to a pair of equal $k_F$ although the densities are different (marked with a cross in (c)). The loci of coinciding $k_F$ and $v_F$ values are shown in (c) and (d), respectively. Solid and dashed lines indicate coupling between equivalent and non-equivalent branches of the dispersion curves.

FIG. 3. Transresistivity in a coupled 2DHG/2DEG system as function of the respective carrier densities. The barrier thickness is 340 nm, the temperature at $T=5$ K. White areas correspond to $\rho_T = 20 \, m\Omega\square$, the black ones to $7 \, m\Omega\square$. The solid line corresponds to the case of coinciding $k_F$ in the 2DEG and in the heavy hole band.

FIG. 4. Transresistivity as a function of distance between two 2DHGs for $T = 2.8 \, K$ and $7 \, K$, respectively. The carrier density is $3 \cdot 10^{11} \, cm^{-2}$. The full line corresponds to the logarithmic dependence expected for phonon coupling. The dashed line is expected for plasmonic coupling.

FIG. 5. Lower panel: $\rho_T$ as function of a perpendicular magnetic field $B$ at different temperatures. The sample contains a 40 nm barrier and has matched densities of $2.5 \cdot 10^{11} \, cm^{-2}$. Upper panel: corresponding longitudinal resistances of the lower layer.
Distance (nm)

$\rho_r / T^2 (\Omega/K^2)$

- $T = 7\,\text{K}$
- $T = 2.8\,\text{K}$

Plasmons

Phonons
