Frictional drag between coupled two-dimensional hole gases in GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructures

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We report on measurements of the drag effect between coupled two-dimensional 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. We make use of the nonparabolicity of the hole-dispersion curves to tune the Fermi wave vector and the Fermi velocity separately. With this technique we find that the frictional drag is mainly due to phonon coupling.

I. INTRODUCTION

The role of the different coupling mechanisms between two closely spaced two-dimensional (2D) charge systems in semiconductors has recently generated much interest. Even if tunneling between the layers can be neglected, the layers are coupled by electron-electron interactions, which lead to a transfer of momenta and a frictional drag between them. The drag force can be measured by passing a drive current I_{drive} through one layer and measuring the resulting voltage drop V_{drag} in the other one.[1] The coupling strength is usually stated as the transresistivity $\rho_T=(W/L)(V_{drag}/I_{drive})$, where W/L is the width to length ratio of the sample. The transresistivity has been derived theoretically based on the random-phase approximation (RPA) and is found to depend on the imaginary parts of the susceptibilities of the two layers χ_1 and χ_2, on the interlayer interaction V_{12}, and on the dielectric constant ϵ_{12} of the combined system:[2,3]

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

Two-dimensional electron gases (2DEG's) in GaAs/$Al_xGa_{1-x}As$ heterostructures in zero magnetic field have been found to couple via Coulomb interaction,[1,3] via the excitation of coupled plasmons,[4] and via the exchange of phonons with $q\approx 2k_F$.[5] At zero magnetic fields the pure Coulomb coupling is weak compared with the phonon coupling except for very closely spaced layers. At temperatures exceeding about $0.2T_F$ coupled plasmon modes are excited at small q and enhance the Coulomb coupling. 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 the phonon interaction may also be enhanced by coupled electron-phonon modes leading to a vanishing of ϵ_{12} around $q=2k_F$.[6] No evidence for the existence of these coupled modes has been reported yet.[7]

No experimental work has been published on the frictional drag between two 2D hole gases (2DHG's). An important difference between hole and electron gases is the greatly reduced Fermi temperature of the hole gases due to the large effective masses of the holes. As a consequence the cross-over to the plasmon coupling ($0.2T_F\approx 5$ K for the holes) could already occur at a temperature which is comparable to a typical Bloch-Grüneisen temperature of several kelvins. (The Bloch-Grüneisen temperature denotes the temperature range in which the phonon interaction is most effective, i.e., the ratio ρ_T/T^2 is at a maximum.[5]) Therefore, for hole gases, Coulomb coupling and phonon coupling cannot easily be distinguished from each other by the different temperature dependences, as is possible in the coupled electron systems. However, hole systems offer a unique possibility to discriminate between the different mechanisms because their energy dispersion curves are nonparabolic. Moreover, this nonparabolicity can be tuned by varying the shape of the quantum wells using external fields or doping. Therefore, these systems offer the possibility to tune both k_F and v_F and to achieve coincidences of either of these quantitites 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 limit the possibility to observe superfluidity in coupled 2DEG/2DHG systems[8] by the reduction of the phase space for Cooper-pair-like scattering.

In this Report we describe measurements of the frictional drag between two 2DHG's as well as more detailed results on coupled 2DEG/2DHG systems. In both cases, the frictional drag is measured as a function of the charge densities in the two layers. We also present data on samples having widely varying barrier thicknesses and will discuss the effects of temperature and of magnetic field. We find 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.

II. EXPERIMENTAL DETAILS

The coupled 2DHG samples are prepared in two 20 nm thick quantum wells in GaAs/$Al_xGa_{1-x}As$ 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 $Al_{0.3}Ga_{0.7}As$ 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

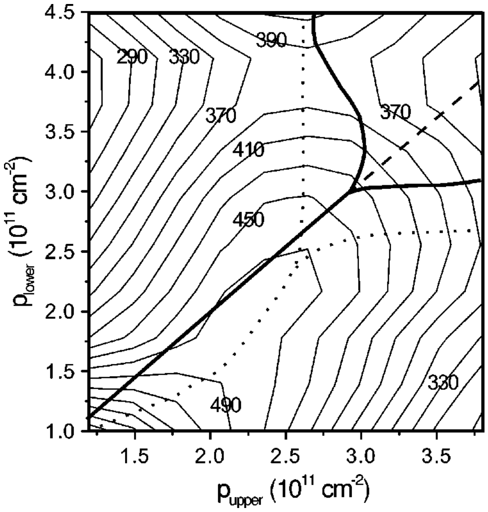

FIG. 1. Contour plot of the transresistivity as function of the carrier densities in the upper (p_{upper}) and the lower (p_{lower}) 2DHG at $T=2.8$ K. The barrier thickness is 140 nm. The numbers give the transresistivity in m$\Omega_{\square}$. The dotted lines run along the ''ridges'' of maximal ρ_T. The heavy lines show the locus of coinciding k_F values in equivalent subbands in the two layers. The dashed line (partially covered by the solid line) corresponds to the condition of equal density in the two layers.

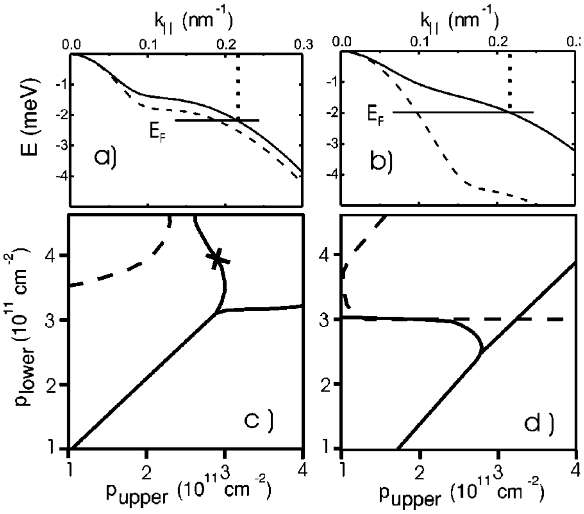

FIG. 2. Dispersion curves of the lower (a) and the upper (b) 2DHG. Identical k_F values are possible even if the densities are different. The loci of coinciding k_F and v_F values are shown in (c) and (d), respectively. Solid and dashed lines indicate coupling between equivalent and nonequivalent branches of the dispersion curves. The dispersion curves of (a) and (b) correspond to densities marked with a cross in (c). The parameters are those of the sample of Fig. 1.

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.[9] 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 independent variation of the carrier densities. Typical hole mobilities at 4K are between 40 000 cm^2/V s and 80 000 cm^2/V s, which are reasonably good values for hole gases on (001) surfaces. The hole concentration can typically be varied from zero to about 5×10^{11} cm^{-2}. Coupled 2DHG/2DEG systems are also produced by modulation doping,[11] which does, however, not allow one to produce barriers as narrow as the nonequilibrium technique of Sivan *et al.*[2]

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 techniques 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 inmeasurably small and cannot influence the signal. Second, the linearity between drag voltage and drive current value is confirmed, as is the fact that identical signals are found if the drive current is passed through either of the two layers and the drag is measured in the other. Measurements are done in a standard cryostat at temperatures between 1.5 and 10 K and in magnetic fields up to 11 T.

III. RESULTS

A. Drag between coupled 2D hole gases

First, we present data on the dependence of the transresistivity, ρ_T, on the hole concentrations. The respective densities are determined by Shubnikov–de Haas measurements at 1.5 K. In Fig. 1 we show ρ_T as a contour plot at 2.8 K as a function of the upper and lower hole densities for a coupled 2DHG sample. The barrier with total thickness of $d=140$ nm$Al_{0.3}Ga_{0.7}As$ contains a 20 nm thick C-doping layer separated 20 nm from the bottom 2DHG. In comparison to coupled 2DEG structures we find a rather complicated dependence of ρ_T on the densities in the two layers. Particularly remarkable is the fact that there is no symmetry in the data with respect to interchange of the two densities p_{upper} and p_{lower}. At small densities in both layers ($\leqslant 3\times10^{11}$ cm^{-2}) the maximal coupling strength is found along a ''ridge'' (marked by dots) running just below the line of equal densities in the two layers (dashed line). At higher densities, however, this ridge splits into two ridges that 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 the consequence of the asymmetric doping of the two wells, because it is also seen in the other asymmetrically doped samples. In contrast, in symetrically doped samples, we find a very broad maximum of the coupling centered around the line of equal densities.[10]

The asymmetric doping leads to an effective electric field in the respective quantum wells that causes the splitting of the highest hole subband into two. This effect has recently been studied in detail in just one hole layer.[12] 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 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 4×4 $k\cdot p$ method. Examples are shown in Figs. 2(a) and 2(b). k_F of one branch of the dispersion curves is identical for the two layers, although their densities are out of balance. The loci of identical k_F and of identical v_F are plotted in Figs. 2(c) and 2(d), respectively. Only the [110] direction is used for this analysis. Using the [100] direction does not change result of this analysis signifi-

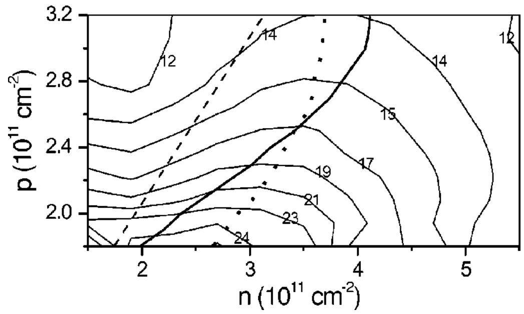

FIG. 3. Transresistivity in a coupled 2DHG/2DEG system as function of the respective carrier densities. The barrier thickness is 340 nm, the temperature $T=5$ K. The numbers give the transresistivity in m$\Omega_{\square}$. The solid line corresponds to the case of coinciding k_F in the 2DEG and in the heavy hole band. The dashed line marks the equal density condition.

cantly. The cross marks the case of Figs. 2(a) and 2(b). In Figs. 2(c) and 2(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 possibility of coupling between bands of different quantum numbers lies far outside of the plot range.

Comparison of these plots with the data of Fig. 1 shows that only the phonon coupling between the hole bands with identical quantum numbers is in overall agreement with experimental data. In Fig. 1 the calculated locus of equal k_F values in the equivalent bands is indicated as a solid line. At small densities ($<2.5\times10^{11}$ cm^{-2}) in both layers, one cannot draw a clear conclusion from this comparison, and it is possible that in the small density regime the Coulomb interaction is more important. We conclude therefore that phonon exchange is the main source of coupling between the hole layers over most of the studied density regimes. The fact that only identical branches of the hole dispersion curves couple with each other is unexpected at first sight. It is most likely due to the acoustical anisotropy of the GaAs, which allows only certain phonon modes (e.g. longitudinal or transversely polarized ones) to couple to a given branch of the dispersion curves.[13]

B. Drag in the 2DEG/2DHG system

Similar experimental data have been obtained in a coupled 2DEG/2DHG system with a barrier of 340 nm. The transresistance as a function of hole and electron concentration is shown in Fig. 3. These data are obtained at 5 K. As in the case of coupled hole gases one finds 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. The different effective masses of the electrons and holes lead to lines of equal v_F values that are far outside the plot range.

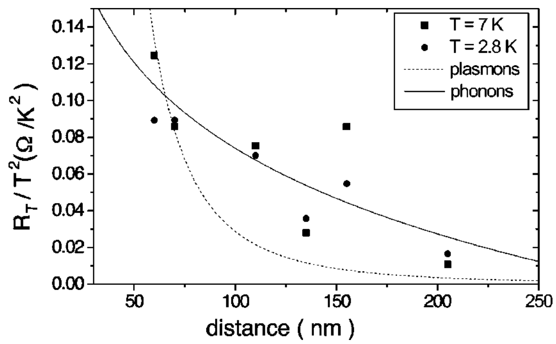

FIG. 4. Transresisistivity as a function of distance between two 2DHG's for $T=2.8$ K and 7 K, respectively. The carrier density is 3×10^{11} cm^{-2}. The full line corresponds to the logarithmic dependence expected for phonon coupling. The dashed line $\rho_T\propto d_{eff}^{-3}$ is expected for plasmonic coupling. The two curves are fitted to the 2.8 K data.

C. Role of barrier thickness

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 ρ_T/T^2 for six coupled 2DHG systems for two different temperatures as function of d_{eff} at matched densities of 3×10^{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 figure shows clearly that the logarithmic dependence is a better description of the data although the prefactors of the fits in Fig. 4 are arbitrary. 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 Ref. 6 for the case of damped phonons, gives $l_{ph}\approx300$ 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 molecular beam epitaxy grown layers as observed by atomic force microgropy studies.[14] A similar logarithmic distance dependence has very recently been reported for a series of differently spaced coupled 2DEG's.[7]

D. Drag in the 2DHG/2DHG system in high magnetic field

Finally we investigate the dependence of the transresistivity on perpendicular magnetic fields. In earlier studies in 2DEG/2DEG systems a dramatic increase of ρ_T with magnetic field was observed except right under the quantum Hall effect conditions where ρ_T vanishes.[15] A less dramatic increase was seen in the 2DHG/2DEG systems.[16] The 2DHG/2DHG systems are different because quantization effects are small in most of our magnetic field and temperature regimes. Experimental data are shown in Fig. 5, where ρ_T is plotted as function of a perpendicular magnetic field. The barrier thickness is 40 nm, and the carrier density is 2.5×10^{11} cm^{-2} in both wells. At the lowest temperature, $T=1.5$ K, ρ_T re-

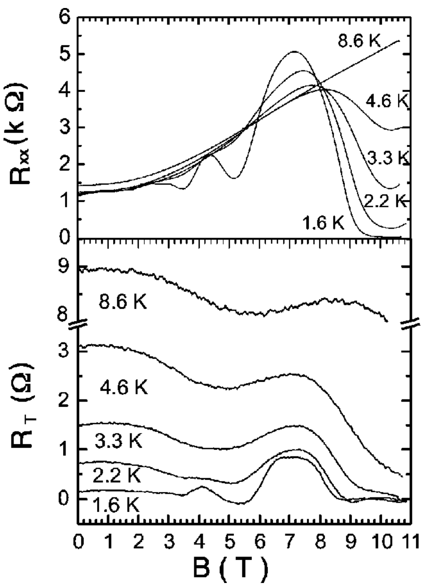

FIG. 5. Lower panel: ρ_T as function of a perpendicular magnetic field B at different temperatures. The sample contains a 40 nm barrier and has matched densities of 2.5×10^{11} cm^{-2}. Upper panel: corresponding longitudinal resistances of the lower layer.

flects the Shubnikov–de Haas oscillations of ρ_{xx} but the increase of the maxima with field is less than those observed in the electron systems.[15,16] At higher temperatures these quantization effects disappear, but now ρ_T shows a *decrease* with *increasing* magnetic field. At even higher temperatures the ρ_T seems to become nearly independent of the magnetic field. Interestingly, this behavior is opposite the behavior of ρ_{xx}, which *increases* with magnetic field in the same experimental range. The general decrease of ρ_T at intermediate temperatures and its flattening at higher temperatures is also observed with densities that 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 Im$\chi(q,\omega)$ at $q\simeq2k_F$ in magnetic fields. At zero magnetic fields this function has a strong maximum near $q\simeq2k_F$ on which most of the analysis of this paper is based. This maximum disappears at large magnetic fields, as was shown theoretically by Glasser.[17] Thus, the coupling via phonons with $q\simeq2k_F$ is weakened in a magnetic field. At quantizing fields that correspond to the usual situation in systems involving electrons, this argument is no longer applicable because other types of interactions are dominant.[16]

IV. CONCLUSIONS

In conclusion we report 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 and establish that the coupling mechanism over most of our parameter range is dominated by phonon coupling at wave vectors $\simeq2k_F$. 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 the theoretical prediction of Bønsager *et al.*[6] about the phonon exchange. 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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