Confinement symmetry, mobility anisotropy, and metallic behavior in (311)A GaAs 2D holes

S. J. Papadakis, E. P. De Poortere, and M. Shayegan

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA.

(March 21, 2022)

We study two dimensional hole systems confined to GaAs quantum wells grown on the (311)A surface of GaAs substrates. Such samples exhibit an in-plane mobility anisotropy. At constant 2D hole density, we vary the symmetry of the quantum well potential and measure the temperature dependence of the resistivity along two different current directions, in a regime where the samples exhibit metallic behavior. The symmetry has a significant and non-trivial effect on the metallic behavior. Moreover, differences between the temperature-dependence of the resistivity along the two mobility directions point to specific scattering mechanisms being important in the expression of the metallic behavior.

The unexpected metallic behavior first observed in an Si/SiO$_2$ two-dimensional (2D) electron system [1], and subsequently in many other 2D systems [2,3] has generated significant interest. We study the metallic behavior in 2D hole systems confined to GaAs quantum wells (QWs) grown on the (311)A surface of GaAs substrates. The data we report demonstrates that both the QW symmetry and the in-plane mobility anisotropy of (311)A GaAs samples have significant effects on the low-temperature behavior of the resistivity $\rho$ over a large range of densities.

Hole systems in GaAs QWs have a large spin-orbit interaction, which in the presence of the inversion asymmetries of the zincblende crystal structure and of the confining potential, causes substantial zero-magnetic-field spin-splitting [3,4]. Using metal gates placed both above and below the QW, we tune the symmetry of the QW confinement potential, and therefore the spin-splitting, while keeping the density constant [5]. Our goal is to determine the effect of spin-splitting on the temperature-$T$ dependence of $\rho$.

GaAs (311)A samples also exhibit an in-plane mobility anisotropy. The anisotropy is caused by irregular corrugations that form at the interfaces between the GaAs QW and the AlGaAs barriers on either side [4,5]. They run parallel to the [233] direction, causing the mobility along the [01$\bar{1}$] direction to be significantly smaller than the mobility along the [233] direction. Transport studies suggest that the scattering mechanisms for current ($I$) along the two directions have significant differences [4]: the mobility of the [01$\bar{1}$] direction is limited primarily by interface-roughness scattering, while the mobility of the [233] direction is limited by remote ionized impurities. In order to study the transport properties along both mobility directions simultaneously, we patterned all of our samples with the Hall bar of Fig. 1.

Our samples are grown by molecular beam epitaxy on undoped (311)A GaAs substrates, and each consists of a 200 A-wide GaAs QW flanked by AlGaAs barriers which are selectively doped with Si. They are lithographically patterned with the Hall bar shown schematically in Fig. 1 and have metal front and back gates. Measurements are done in a dilution refrigerator at temperatures from 0.8 K to 25 mK and in perpendicular magnetic fields up to 16 T. We use the low-frequency lock-in technique to measure the longitudinal ($\rho$) and Hall resistivities. Experiments are done on samples from four different wafers at 2D hole densities $\rho$ from $3.3 \times 10^{11}$ to $2.5 \times 10^{10}$ cm$^{-2}$. These $\rho$ range from deep in the metallic regime to near the apparent metal-insulator transition [4,5]. Typical 25 mK mobilities are around 50 m$^2$/Vs. We concentrate here on data from two samples in the low-$\rho$ regime ($\rho \leq 1.2 \times 10^{11}$ cm$^{-2}$); higher-$\rho$ data are presented elsewhere [4].

FIG. 1. L-shaped Hall bar with which all samples are patterned. It allows simultaneous measurement of resistivity along the [233] and [01$\bar{1}$] directions.
gate leakage. In some samples, this was done at multiple $p$. While the above method allows accurate calculation of the change in $E_{\perp}$ when gate voltages are changed, it does not directly measure the absolute magnitude of $E_{\perp}$. In the higher $p$ measurements, the absolute magnitude can be determined directly from the Shubnikov-de Haas oscillations $[6]$. In the lower $p$ measurements, where the sample quality and the magnitude of the spin-splitting are reduced, we estimate it from the growth parameters of the samples $[8]$, from mobility changes, and from the magnitude of a magnetoresistance feature at low magnetic field $[8]$. We believe our estimate to be accurate to within $\pm 1.5$ kV/cm. In our study, we define $E_{\perp}$ as positive (negative) if it points to the surface (substrate).

Here we report data for $E_{\perp} \leq 0$; in cases where we have been able to explore the $E_{\perp} > 0$ regime $[8]$, we find the $T$-dependence of $\rho$ to be nearly symmetric for $E_{\perp} < 0$ and $E_{\perp} > 0$.

Overall, the data show that over a large range of $p$, the spin-splitting has a significant effect on the magnetic field $[8,18]$. We believe our estimate to be accurate to within $\pm 1.5$ kV/cm. In cases where we have been able to explore the $E_{\perp} > 0$ regime $[8]$, we find the $T$-dependence of $\rho$ to be nearly symmetric for $E_{\perp} < 0$ and $E_{\perp} > 0$.

As an example, we start with data from sample M367 at $p = 8.5 \times 10^{10}$ cm$^{-2}$ (Fig. 2a), after which we will show that similar effects are observed over a wide range of $p$. Concentrating on the top part of Fig. 2a, we see that increasing $|E_{\perp}|$ at constant density causes the change in $\rho$ to become larger as $T$ is increased from 25 mK to 0.8 K $[8]$. However, changing $E_{\perp}$ also affects the resistivity at 25 mK ($\rho_0$), and it has been suggested that these changes in $\rho_0$ are responsible for the increased $T$-dependence $[19]$. Looking at data from both arms of the Hall bar, we are able to determine that it is mainly the changes in spin-splitting, not in $\rho_0$, that are causing the changes in the $T$-dependence of $\rho$. The traces in the top part of Fig. 2a (above 140 $\Omega$/sq.) are for the [011] direction, and those in the bottom part are for [233]. As $|E_{\perp}|$ is increased, $\rho_0$ for the [011] direction traces increases, but it decreases for the [233] direction. However, it is clear that for both current directions, as $|E_{\perp}|$ becomes larger the increase in $\rho$ with $T$ also becomes larger. Figure 2b quantifies these statements. The upper two panels show the fractional change in $\rho$, $\Delta \rho / \rho_0$, as $T$ is increased from 25 mK to $\sim 0.8$ K. Clearly the data from both $I$ directions have the same behavior as $|E_{\perp}|$ is increased. The lower two panels show the two $\rho_0$, which do not have the same behavior as a function of $E_{\perp}$.

These data provide strong evidence that the changes in $\Delta \rho / \rho_0$ with $E_{\perp}$ are not driven simply by the change in the sample disorder as the QW symmetry is varied. They suggest that the QW symmetry plays a role in the $T$-dependence of $\rho$ through its effect on the spin-splitting. We do not mean to imply by this statement that the value of $\rho_0$ does not have an effect on the $T$-dependence of $\rho$. On the contrary we expect that it does, for in the limit of a highly disordered sample with very large $\rho_0$ we expect conventional insulating (strongly localized) behavior. However, the data of Fig. 2b do show that, for small changes in $\rho_0$, the more important parameter is the symmetry of the QW.

An interesting feature of the data, related to the differences between the two mobility directions, is that the shapes of the curves in the top two panels of Fig. 2b are very similar, but the magnitudes are different. For

![FIG. 2. (a) Selected raw data showing the $T$-dependence of $\rho$ for both current directions. The top section shows data for $\rho_{||} [011]$ and the bottom section for $\rho_{||} [233]$. Both sections are plotted on the same scale. (b) $\Delta \rho / \rho_0$ (the fractional change in $\rho$ from $T = 25$ mK to 0.8 K) and $\rho_0$ for $E_{\perp}$ plotted vs. $E_{\perp}$, shown for the two measured $I$-directions. The data show that the changes in $E_{\perp}$ are not due simply to changes in $\rho_0$.]

(FIG. 2. a) Selected raw data showing the $T$-dependence of $\rho$ for both current directions. The top section shows data for $\rho_{||} [011]$ and the bottom section for $\rho_{||} [233]$. Both sections are plotted on the same scale. (b) $\Delta \rho / \rho_0$ (the fractional change in $\rho$ from $T = 25$ mK to 0.8 K) and $\rho_0$ for $E_{\perp}$ plotted vs. $E_{\perp}$, shown for the two measured $I$-directions. The data show that the changes in $E_{\perp}$ are not due simply to changes in $\rho_0$.)

(a): M367 $p = 8.5 \times 10^{10}$ cm$^{-2}$

$E_{\perp}$ (kV/cm):

- $0$
- $-4.5$
- $-8.9$
- $-14.9$

$\rho_{||} (\Omega$/sq.)

$I_{||} [01T]$

- $0$
- $0.04$
- $0.08$
- $0.12$

$b$: $\rho_{||} (\Omega$/sq.)

$I_{||} [01T]$

- $0$ (a)
a given $E_\perp$, the spin-splitting is the same regardless of the $I$-direction in the sample, but the $T$-dependencies of $\rho$ are larger, in both absolute magnitude and percent change, for the [011] direction than for [233]. This emphasizes the subtle nature of the effect of spin-splitting on the $T$-dependence of $\rho$. The relationship between the spin-splitting and the magnitude of the $T$-dependence of $\rho$ is modified differently by the different scattering mechanisms along the two directions.

We now discuss data from a broad range of $p$. Since plotting the raw data, as in Fig. 2a, results in the traces crossing each other due to their different $\rho_0$, in Fig. 3 we plot $\rho/\rho_0$ to make comparison of the traces more straightforward. As a function of $p$, the data behave qualitatively as has been observed in previous experiments [233]: for the highest $p$ ($p \geq 7.0 \times 10^{10}$ cm$^{-2}$), $\rho$ monotonically increases with increasing $T$ without inflection, and a reduction in $p$ leads to a stronger $T$-dependence of $\rho$; for intermediate $p$ ($p = 3.3 \times 10^{10}$ cm$^{-2}$), an inflection point appears in the measured $T$ range; and for the lowest $p$ ($p = 2.5 \times 10^{10}$ cm$^{-2}$), $\rho$ shows both an inflection point and a maximum in the measured $T$ range. If $p$ were decreased further, we would expect conventional insulating behavior [233].

At a given $p$, we can see that the effect on $\rho$ vs. $T$ of an increase in $|E_\perp|$ is qualitatively similar to the effect of a reduction in $p$. For the higher $p$ data ($p \geq 7.0 \times 10^{10}$ cm$^{-2}$), increasing $|E_\perp|$ increases the magnitude of the $T$-dependence of $\rho$. In the $p = 3.3 \times 10^{10}$ cm$^{-2}$ data, increasing $|E_\perp|$ both strengthens the $T$-dependence of $\rho$ and moves the inflection point to lower $T$. In the $p = 2.5 \times 10^{10}$ cm$^{-2}$ data, increasing $|E_\perp|$ causes both the inflection point and the maximum to shift to lower $T$ and leads to weaker overall $T$-dependence of $\rho$ (again qualitatively similar to the effect of reducing $p$ in this regime). An interesting point is that there is likely a $p$
where $\rho$ may show very similar fractional change with $T$ as $E_\perp$ is varied. There is another possible reason for the different behavior in the lowest $p$ data: at $p = 2.5 \times 10^{10}$ cm$^{-2}$, $\rho_0$ increases significantly more as a function of $E_\perp$ than it does at the other $p$.

As was done in the data at $p = 8.5 \times 10^{10}$ cm$^{-2}$ (Fig. 2), at the other $p$ differences in the behaviors of $\rho_0$ vs. $E_\perp$ from the two arms of the Hall bar can be used to separate the effects of $E_\perp$ and $\rho_0$. Along the [011] direction, it is typical for $\rho_0$ to increase as $E_\perp$ is increased. This is because interface roughness scattering is the limiting factor for the mobility [4]. As the QW is made more asymmetric, the hole wavefunction is pushed towards one edge of the QW, so it is more affected by the interface roughness, and $\rho_0$ increases. Along the [233] direction, however, the interface roughness plays a much smaller role, so $\rho_0$ is limited by ionized impurity scattering.

While the behavior of $\rho_0$ along [011] as a function of $E_\perp$ in all samples is qualitatively similar to that in Fig. 2, the behavior of $\rho_0$ along [233] varies significantly with sample and $p$. For example, it is non-monotonic in sample M353 at $p = 1.2 \times 10^{11}$ cm$^{-2}$, and in M367 at $p = 8.5$ and $3.3 \times 10^{10}$ cm$^{-2}$ [20]. In all samples at all measured $p$, $\Delta\rho^2/\rho_0$ has the same qualitative dependence on $E_\perp$ in both $I$ directions.

The data presented in this report, along with those reported in Refs. [8] and [18], show that for seven densities, measured in samples from four different wafers, covering more than an order of magnitude of $p$ ($2.5 \times 10^{10}$ to $3.3 \times 10^{11}$ cm$^{-2}$), the asymmetry of the QW, and therefore the magnitude of the spin-splitting, has an effect on the low-$T$ temperature-dependence of $\rho$. In the range $p \geq 3.3 \times 10^{10}$ cm$^{-2}$, as $p$ is reduced the magnitude of the $T$-dependence of $\rho$ becomes larger. Interestingly, in this range the effect of $E_\perp$ also becomes larger, in that the same $E_\perp$ causes a larger increase in $\rho/\rho_0$ with increasing $T$. This is especially noteworthy because the spin-splitting is becoming smaller as $p$ is reduced, so the effect of spin-splitting on the metallic behavior is becoming much stronger as $p$ is reduced from $3.3 \times 10^{11}$ to $3.3 \times 10^{10}$ cm$^{-2}$ [21]. Note also that the data of Fig. 2 imply that the effect of $E_\perp$ is strongest at $p$ where the metallic behavior is most pronounced. This emphasizes the link between the spin-splitting and the metallic behavior in GaAs 2D holes [38].

In summary our data reveal two specific parameters which affect the $T$-dependence of $\rho$ significantly. First, the symmetry of the QW plays a role through spin-splitting in both the magnitude of the change in $\rho$ with $T$ and in the shape of the curve. Second, the absolute and fractional changes in $\rho$ are quantitatively different for the two mobility directions, pointing out that interface roughness scattering also has an important role. A model including only ionized impurity scattering has reproduced some of the qualitative features of $\rho$ vs. $T$ [24]. We propose that the $T$-dependencies of both inter-spin-subband scattering and interface roughness scattering should also be included in calculations which attempt to explain $\rho$ vs. $T$ data. The different dependencies of $\rho$ on the various parameters reveal that the metallic behavior cannot be simply characterized by any overall parameter such as mean free path or Fermi energy [24].

We gratefully acknowledge the NSF and DOE for supporting this work.

[1] S. V. Kravchenko, G. V. Kravchenko, and J. E. Furneaux, Phys. Rev. B 50, 8039 (1994).
[2] D. Popović, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. 79, 1543 (1997).
[3] P. T. Coleridge, R. L. Williams, Y. Feng, and P. Zawadzki, Phys. Rev. B 56, R12764 (1997).
[4] J. Lam, M. D’Iorio, D. Brown, and H. Lafontaine, Phys. Rev. B 56, R12741 (1997).
[5] Y. Hanein et al., Phys. Rev. Lett. 80, 1288 (1998).
[6] M. Y. Simmons et al., Phys. Rev. Lett. 80, 1292 (1998).
[7] S. J. Papadakis and M. Shayegan, Phys. Rev. B 57, R15068 (1998).
[8] S. J. Papadakis et al., Science 283, 2056 (1999).
[9] S. J. Papadakis et al., Physica E 6, 258 (2000).
[10] S. S. Murzin, S. I. Dorozhkin, G. Landwehr, and A. C. Gossard, JETP Lett. 67, 113 (1998).
[11] Y. Yaish et al., Phys. Rev. Lett. 84, 4954 (2000).
[12] A. P. Mills, Jr., A. P. Ramirez, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 83, 2805 (1999).
[13] J. P. Eisenstein et al., Phys. Rev. Lett. 53, 2579 (1984); Yu. A. Bychkov and E. I Rashba, Pisma Zh. Eksp. Teor. Fiz. 39, 66 (1984) [JETP Lett. 39, 78 (1984)]. For a review, see U. Rössler, F. Malcher, and G. Lommer, in High Magnetic Fields in Semiconductor Physics II, edited by G. Landwehr (Springer, Berlin, 1989) [Springer Series in Solid State Sciences, 87] p. 376.
[14] J. P. Lu et al., Phys. Rev. Lett. 81, 1282 (1998).
[15] R. Nötzel et al., Phys. Rev. B 45, 3507 (1992).
[16] M. Wasserman et al., Phys. Rev. B 51, 14721 (1995).
[17] J. J. Heremans, M. B. Santos, K. Hirakawa, and M. Shayegan, J. Appl. Phys. 76, 1980 (1994).
[18] S. J. Papadakis, Ph.D. thesis, Princeton University, Princeton, NJ, 2000.
[19] A. R. Hamilton, M. Y. Simmons, M. Pepper, and D. A. Ritchie, cond-mat/0003293.
[20] Note that the measured $\rho_0$ are very accurate as they result from averaging $\rho$ at base-$T$ for a long period of time.
[21] S. J. Papadakis, E. P. De Poortere, M. Shayegan, and R. Winkler, cond-mat/0006497.
[22] S. J. Papadakis, E. P. De Poortere, M. Shayegan, and R. Winkler, Phys. Rev. Lett. 84, 5592 (2000).
[23] S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. 83, 164 (1999).
[24] This point has also been made using data from 2D electrons in Si [X. G. Feng, D. Popović, and S. Washburn, Phys. Rev. Lett. 83, 368 (1999)].