Dependence of Effective Mass on Spin and Valley Degrees of Freedom

T. Gokmen, Medini Padmanabhan, and M. Shayegan

Department of Electrical Engineering, Princeton University, Princeton, NJ 08544

(Dated: October 11, 2008)

We measure the effective mass \(m^*\) of interacting two-dimensional electrons confined to an AlAs quantum well while we change the conduction-band valley occupation and the spin polarization via the application of strain and magnetic field, respectively. Compared to its band value, \(m^*\) is enhanced unless the electrons are fully valley and spin polarized. Incidentally, in the fully spin- and valley-polarized regime, the electron system exhibits an insulating behavior.

PACS numbers:

In Fermi liquid theory, interacting electrons can be treated as non-interacting quasi-particles with a renormalized effective mass \(m^*\). The parameter \(m^*\) has been studied extensively for various two-dimensional electron systems (2DESs) as a function of interaction strength, which is characterized by the ratio \(r_s\) of the Coulomb energy to Fermi energy. In the highly interacting, dilute regime \((r_s > 3)\), \(m^*\) is typically significantly enhanced compared to its band value \(m_0\) and tends to increase with increasing \(r_s\). A question of particular interest is the dependence of \(m^*\) on the 2DES electrons’ spin and valley degrees of freedom as these affect the exchange interaction. Measurements on 2DESs in Si-MOSFETs (metal-oxide-semiconductor field effect transistors), have indicated that the \(m^*\) enhancement is independent of the degree of spin-polarization \(S\). On the other hand, recent \(m^*\) measurements for 2D electrons confined to highly strained AlAs quantum wells revealed that, when the 2DES is fully spin-polarized, \(m^*\) is suppressed down to values near or even slightly below \(m_0\). The reason for this apparent discrepancy might be that the 2D electrons in the Si-MOSFET case occupy two conduction-band valleys \(\bar{v}\) while the 2DES studied in Ref. \(\bar{3}\) is a single-valley system. Here we experimentally study \(m^*\) in an AlAs 2DES while we tune the valley and spin degrees of freedom in a single sample. The results, summarized in Fig. 1, provide direct and conclusive evidence that the valley and spin degrees of freedom are indeed both important in \(m^*\) re-normalization. If the electrons are only partially valley and/or spin polarized, then their \(m^*\) is enhanced with respect to \(m_0\). But if they are fully valley and spin polarized, then \(m^*\) is suppressed. The fully spin and valley polarized regime is incidentally also the regime where the 2DES shows an insulating behavior.

We studied a high-mobility 2DES confined to an 11 nm-thick, modulation-doped AlAs layer, grown by molecular beam epitaxy on a (001) GaAs substrate \(\bar{11}\). In this sample, the 2D electrons occupy two energetically degenerate conduction-band valleys with elliptical Fermi contours \(\bar{11}\), each centered at an X point of the Brillouin zone, and with an anisotropic mass (longitudinal mass \(m_l = 1.05\) and transverse mass \(m_t = 0.20\), in units of free electron mass, \(m_e\)). The two valleys have their major axes either along the [100] or the [010] crystal directions; we denote them as [100] and [010] valleys, respectively. Their degeneracy can be lifted by applying a symmetry breaking strain \(\epsilon = \epsilon_{[100]} - \epsilon_{[010]}\), where \(\epsilon_{[100]}\) and \(\epsilon_{[010]}\) are the strain values along the [100] and [010] directions. Electrons are transferred from the [100] valley to the [010] valley for positive \(\epsilon\) and vice versa for negative \(\epsilon\). We control the valley occupation using \(\epsilon\) and the spin occupation (polarization) via the application of magnetic field. We studied several samples; here we focus on data from one sample patterned with a \(60 \times 60 \mu m^2\) square mesa whose edges are aligned along the [100] and [010] directions, and the current is passed along [010]. The sample is glued to the side of a stacked piezo actuator allowing us to apply in-plane strain which can be controlled and measured \textit{in situ} \(\bar{11}\). The magneto-resistance measurements were performed in a dilution refrigerator with...
a base temperature \((T)\) of 0.02 K and equipped with a tilting stage, allowing the angle \(\theta\) between the sample normal and the magnetic field to be varied \textit{in situ}.

The \(B_{∥}\) vs. \(\epsilon\) phase diagram of Fig. 1 highlights the important features of our results \((B_{∥})\) is the magnetic field applied parallel to the 2D plane. In this figure, the thick, solid lines mark the boundaries between the four possible spin and valley subband occupations for our sample, which had a density \(n = 3.8 \times 10^{11} \text{ cm}^{-2}\); we denote the occupations by \((s=2, v=2), (s=2, v=1), (s=1, v=2)\) and \((s=1, v=1)\), where \(s\) and \(v\) stand for spin and valley, respectively \[13\]. We determined these boundaries from measurements of sample resistance \((R)\) vs. either \(B_{∥}\) or \(\epsilon\) while the other parameter is kept fixed. Examples of such data are shown in Fig. 2 at two temperatures. For each pair of traces, \(\epsilon\) is kept constant while for each pair in (b) \(B_{∥}\) is kept fixed at the indicated values.

In the remainder of the paper we describe our determination of \(m^*\), from the \(T\)-dependence of the Shubnikov-de Haas (SdH) oscillations, in different quadrants of Fig. 1. Figure 3 shows the data for the \((s=1, v=2)\) case which were taken at \(\theta = 74.8^\circ\) and \(\epsilon = -0.16 \times 10^{-4}\). These values for \(\theta\) and \(\epsilon\) were chosen carefully so that the lowest eight Landau levels (LLs) are spin polarized and the two valleys have equal densities at the LL fill-factor \(\nu = 6\), as shown in Fig. 3(b). Figure 3(a) shows the SdH oscillation near \(\nu = 6\) at several \(T\). To deduce \(m^*\), we analyzed the \(T\)-dependence of the am-
FIG. 4: (Color online) Magneto-resistance traces, Dingle fits, and energy level diagrams for (s=1, \nu=1), (s=2, \nu=1) and (s=2, \nu=2). The black, red and green traces were taken at (a) 0.02, 0.39, 1.03; (b) 0.02, 0.60, 0.87; (c) 0.02, 0.24, 0.39K.

The data for the (s=1, \nu=1) case are shown in Fig. 4(a). Here \epsilon is large enough so that only the [010] valley is occupied. Moreover, by tilting the sample to a sufficiently large \theta we ensure that the lowest seven LLs are spin polarized, as indicated in Fig. 4(a) energy level diagram. Note the qualitative similarity of the field traces in Figs. 4(a) and 2(b): R shows a pronounced increase with field and then saturates above \sim 11T once the 2DES is completely spin polarized. Since the sample is not completely parallel to the field in Fig. 4(a), however, there are SdH oscillations which become well resolved after the full spin polarization; these are the oscillations from which we deduce \nu^*. The inset to Fig. 4(a) shows the T-dependence of the SdH oscillation centered around \nu=5. From the fit to the Dingle expression we obtain \nu^*=0.62m_b at this \nu=5; data at \nu=6 yield \nu^*=0.60m_b.

Figure 4(b) shows data for the (s=2, \nu=1) case. Here \epsilon is chosen large enough so that the system is completely valley polarized and \theta is adjusted such that the LLs at odd \nu are at coincidence. The corresponding LL energy diagram is shown in Fig. 4(b) inset. Consistent with this diagram, in Fig. 4(b) traces, resistance minima at even \nu are strong while the minima at odd \nu are either weak or entirely absent (at high \nu), or are accompanied by spikes (e.g., at \nu=3). By fitting the amplitude of the SdH oscillations near \nu=8, 10, and 12 to the Dingle expression, we obtain \nu^*=1.16, 1.22, and 1.22m_b, respectively (see Fig. 4(b) inset as an example). This observation implies that \nu^* does not depend on the spin polarization (P_s), defined as the difference between the spin up and down populations divided by the total electron density; such independence is not surprising since in the range of 8 \leq \nu \leq 12, P_s changes only from 0.17 to 0.25.

In Fig. 4(c), we show data for (s=2, \nu=2). Here \epsilon = 0 and \theta is chosen so that the spin-up and spin-down LLs are at coincidence, as illustrated in the energy diagram in Fig. 4(c). The strongest resistance minima are observed
at $\nu = 8$, 12, and 16. We obtain $m^* = 1.58m_b$ from the fit of SdH oscillation amplitude around $\nu = 12$ to the Dingle expression, as shown in Fig. 4(c) inset.

In our determination of $m^*$ from the SdH oscillations, we have assumed that $R_o$ and $\tau(q)$ are $T$ independent. It is apparent in Figs. 3-4, however, that $R_o$ has some dependence on $T$. To take this into account, we also analyzed our data by defining $R_o$ as the average resistance value near a SdH oscillation, and assumed that the relative $T$-dependence of $\tau(q)$ is similar to but has half the size of the relative $T$-dependence of $R_o$. The deduced $m^*$ from such analysis are about 10% smaller than the values reported above, indicating that the main conclusions of our study remain intact.

Our results presented in Figs. 3 and 4, and summarized in Fig. 1, provide direct experimental evidence for the dependence of $m^*$ on valley and spin polarization of the 2DES. This is intuitively plausible since $m^*$ renormalization in an interacting 2DES partly stems from the exchange interaction which depends on the spin and valley degrees of freedom. Several features of our data are noteworthy. First, we observe the largest $m^*$ enhancement for the $(s=2, v=2)$ case. As we fully spin polarize the 2DES while keeping $v=2$, we observe little dependence of $m^*$ on spin-polarization. This observation is consistent with the experimental results of Shashkin et al. who reported that $m^*$ does not depend on the degree of spin-polarization in Si-MOSFET 2DESs where the electrons occupy two valleys. Theoretical justification for this independence is provided in Ref. [2] where it is argued that in a two-valley 2DES the dependence of $m^*$ on the spin polarization is likely to be too weak to be experimentally measurable. On the other hand, when we keep $s=2$ and fully valley polarize the 2DES, we observe about 20% reduction in $m^*$. The reason for this reduction is not clear, but we note that the spin and valley degrees of freedom are not identical. Second, data of Fig. 3(f) suggest that, if $s=1$, then there is reduction of $m^*$ with increasing valley polarization [14]. If one treats the spin and valley degrees of freedom as qualitatively similar, this observation is consistent with the theoretical work of Ref. [10] where, for the majority spin electrons, a reduction of $m^*$ with increasing spin polarization has been reported in a single-valley 2DES. Third, we find that $m^*$ is significantly reduced, to values even below $m_b$ when the 2DES is fully spin and valley polarized [3], implying that the exchange interaction is notably different when the spin and valley degrees of freedom are both frozen out.

Finally, our data imply that there may be a link between the $m^*$ suppression and the metal-insulator (MIT) transition observed in our 2DES. As seen in Fig. 1, the strong $m^*$ suppression and the insulating phase both occur in the regime where the 2DES is spin and valley polarized. It is important to note, however, that our $m^*$ data were all taken in the presence of a perpendicular component of the magnetic field. Such a field could suppress the insulating behavior; this can be seen, e.g., in Fig. 4(a) where the MIT observed around $B_p = 9$T in the upper traces of Fig. 2(a) is no longer visible.

In summary, measurements in an AlAs 2DES reveal variations of $m^*$ with spin and valley polarizations. Some of the variations we observe can be qualitatively explained by the existing calculations. A quantitative understanding of our observations, including the apparent link between the $m^*$ suppression and the insulating phase in the fully spin and valley polarized regime, awaits future work.

We thank the NSF for support, D.L. Maslov, S. Das Sarma, and E. Tutuc for helpful discussions. Part of this work was done at the NHMFL, Tallahassee, which is also supported by the NSF. We thank E. Palm, T. Murphy, J. Jaroszynski, S. Hannahs and G. Jones for assistance.

[1] J.L. Smith and P.J. Stiles, Phys. Rev. Lett. 29, 102 (1972).
[2] W. Pan, D.C. Tsui, and B.L. Draper, Phys. Rev. B 59, 10208 (1999).
[3] A.A. Shashkin et al., Phys. Rev. Lett. 91, 046403 (2003).
[4] Y.-W. Tan et al., Phys. Rev. Lett. 94, 016405 (2005).
[5] M. Padmanabhan, T. Gokmen, N.C. Bishop, and M. Shayegan, Phys. Rev. Lett. 101, 026402 (2008).
[6] Y. Kwon, D.M. Ceperley, and R.M. Martin, Phys. Rev. B 50, 1684 (1994).
[7] R. Asgari et al., Phys. Rev. B 71, 045323 (2005).
[8] R. Asgari and B. Tanatar, Phys. Rev. B 74, 075301 (2006).
[9] S. Gangadharaiah and D.L. Maslov, Phys. Rev. Lett. 95, 186801 (2005).
[10] Y. Zhang and S. Das Sarma, Phys. Rev. Lett. 95, 256603 (2005).
[11] M. Shayegan et al., Phys. Stat. Sol. (b) 243, 3629 (2006).
[12] For the $(s=2, v=1)$ case, $r_s = 8.0$ for our sample.
[13] O. Gunawan et al., Nature Physics 3, 388 (2007).
[14] T. Gokmen et al., to be published.
[15] R.B. Dingle, Proc. R. Soc. London A 211, 517 (1952).
[16] O. Gunawan et al., Phys. Rev. Lett. 97, 186404 (2006).
[17] E.P. De Poortere, E. Tutuc, S.J. Papadakis, M. Shayegan, Science 290, 1546 (2000).
[18] According to a theoretical study [Y. Adamov, I.V. Gornyi, and A.D. Mirlin, Phys. Rev. B 73, 045426 (2006)], for short-range scatterers, the relative $T$-dependent correction to $\tau(q)$ is half of the relative correction to the transport scattering time $\tau_T$. We note that the estimated $\tau_T$ in our sample, which is modulation-doped, is 5 to 10 times longer than $\tau(q)$, implying that the dominant source of scattering are the remote ionized impurities. For such long-range scatterers, the $T$-dependence of $\tau_T$ is likely weaker than that of $\tau(q)$, by more than a factor of two [S. Das Sarma, unpublished].
[19] Analogously, one might expect that, when $v=1$, $m^*$ should decrease with increasing spin-polarization. We cannot rule out such possibility since our data is experimentally limited to only a small range of spin polarization $0.17 < P_S < 0.25$. 