In-plane magnetic field dependence of cyclotron relaxation time in a Si two-dimensional electron system

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Cyclotron resonance of two-dimensional electrons is studied for a high-mobility Si/SiGe quantum well in the presence of an in-plane magnetic field, which induces spin polarization. The relaxation time $\tau_{\text{CR}}$ shows a negative in-plane magnetic field dependence, which is similar to that of the transport scattering time $\tau_t$ obtained from dc resistivity. The resonance magnetic field shows an unexpected negative shift with increasing in-plane magnetic field.

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Low-density and strongly correlated two-dimensional (2D) systems have attracted much attention. Metallicity depends on temperature $T$ has been observed in 2D systems where a Wigner-Seitz radius of localization in two dimensions.

Another intriguing feature of low density 2D systems is a dramatic response to a magnetic field parallel to the 2D plane. Strong positive magnetoresistance has been reported for various 2D carrier systems such as Si-metal oxide semiconductor field effect transistors (MOSFETs), silicon dioxide/metaloxide semiconductor magnetoresistance has been reported for various semiconductor magnetoresistance has been reported for various heterojunctions, quantum wells (QWs), and SiGe QWs. It is related to the spin polarization since an unexpected negative shift with increasing in-plane magnetic field.

Recently, Masutomi et al. have performed cyclotron resonance (CR) measurements on high-mobility Si 2D electron systems (2DESs). The relaxation time $\tau_{\text{CR}}$, obtained from the linewidth, was found to be comparable to the transport scattering time $\tau_t$. It increases with decreasing temperature in a fashion similar to $\tau_t$. The results indicate that the scattering time has the metallic $T$ dependence over a wide frequency range. In this work, we study $\tau_{\text{CR}}$ in the presence of an in-plane magnetic field. It decreases as $B_{\parallel}$ increases. The $B_{\parallel}$ dependence is also similar to that of $\tau_t$, which corresponds to the positive magnetoresistance.

The sample was fabricated from the same wafer as the one studied in Ref. 18. It is a Si/SiGe heterostructure with a 20-nm-thick strained Si QW sandwiched between relaxed Si$_{0.8}$Ge$_{0.2}$ layers. The electrons are provided by a Sb-δ-doped layer 20 nm above the channel. The 2D electron concentration $N_e$ was adjusted to 1.13 $\times 10^{15}$ m$^{-2}$ at 20 K with bias voltage $V_B$ = −5.5 V of a p-type Si(001) substrate 2.1 μm below the channel. A two-axis vector magnet system was used to apply independently $B_{\parallel}$ and the perpendicular magnetic field $B_{\perp}$ for CR measurements. Instead of using a bolometer, we observe electron heating in the 2DES under excitation at 100 GHz. A Hall bar sample, whose channel width is 200 μm, was mounted inside an oversized waveguide with an 8-mm bore inserted into a liquid-helium cryostat.

Figure 1 shows $B_{\parallel}$ dependence of $\rho$ at $B_{\perp} = 0$ for different $T$ without millimeter-wave radiation. The in-plane magnetic field is oriented along the Hall bar direction. The critical magnetic field for the full spin polarization ($P = 1$) at $T = 0$ is estimated to be 5.0 T at this density. Arrows indicate calculated values of $B_{\parallel}$ for $P = 0.5$ at each temperature. While $P$ decreases with increasing $T$ for a fixed $B_{\parallel}$, the reduction of $P$ is not significant in this temperature range. In contrast to the case of Si-MOSFETs and p-GaAs/AlGaAs heterojunctions, high-mobility Si 2DESs exhibit apparent metallic behavior even in the spin-polarized regime. In Ref. 8, Okamoto et al. proposed a schematic phase diagram and pointed out the importance of low disorder and the valley

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degree of freedom. The essential role of the valley degree of freedom for the metallic behavior is also reported for an AlAs 2DES.\textsuperscript{15}

Figure 2(a) shows \( B_\perp \) dependence of the longitudinal resistivity \( \rho_{xx} \) at \( B_\parallel = 3.0 \, \text{T} \). The lattice or bath temperature, \( T_\text{L} \), was kept at 1.7 K and the magnetoresistance curves were obtained with and without electromagnetic-wave excitation. We also measured the magnetoresistance at higher temperatures and confirmed that \( T \) dependence of \( \rho_{xx} \) remains metallic in the measurement region. The radiation-induced increase in \( \rho_{xx} \) can be attributed to electron heating. The electron temperature \( T_e \) is evaluated from the data obtained without radiation for \( T_e = T_\text{L} > 1.7 \, \text{K} \). Electron cooling to the lattice is expected to occur via electron-phonon coupling. Heat transfer rate can be obtained experimentally from the dc current-voltage characteristics.\textsuperscript{21,22} Using a sample fabricated from the same wafer, Toyama \textit{et al.} found a \( T^5 \) power law in the range from 0.6 to 8 K.\textsuperscript{23}

The relaxation time is calculated to be 2 ns at 1.7 K, which is much longer than \( \tau_t \), \( \tau_{\text{CR}} \), the period of the electromagnetic wave (= 10 ps), and the dephasing time (~ \( h/k_BT = 4 \, \text{ps} \)). The weakness of the electron-phonon coupling ensures well-defined steady-state temperature \( T_e \) of the electron system. In Fig. 2(b), the CR absorption is shown assuming that it is proportional to \( \Delta T = T_e - T_\text{L} \). The corresponding temperature difference, \( \Delta T \), is indicated on the right axis.

The relaxation time is obtained as \( \tau_{\text{CR}} = B_{\text{CR}}/(\omega \Delta B) \). Here \( B_{\text{CR}} \) is the resonance magnetic field and \( \omega \) is the microwave frequency (\( \omega/2\pi = 100 \, \text{GHz} \)). Although the data of Fig. 3(a) were obtained for a constant \( T_\text{L} \), the difference in \( T_e \) for different \( B_\parallel \) is small since \( \Delta T \) was

\[ \tau_t \approx \frac{\hbar}{8\pi N_e \sigma} \]

\[ \tau_{\text{CR}} \approx \frac{\hbar}{4\pi N_e \sigma} \]

\[ \frac{\Delta T}{T_e} \approx \frac{\hbar}{4\pi N_e \sigma} \]

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kept low and about 0.2 K at the peak for all \( B_|| \). The obtained \( \tau_{\text{CR}} \) exhibits a negative dependence on \( B_|| \). It is similar to that of \( \tau_e \), corresponding to the positive magnetoresistance. This suggests that the scattering time has a negative dependence on the spin polarization over a very wide frequency range from dc to 100 GHz. We believe that the present results, together with those of the present system.

In Fig. 3(b), \( B_{\text{CR}} \) is plotted as a function of \( B_|| \). Unexpectedly, \( B_{\text{CR}} \) deviates from 0.19\( m_e \omega/e \) and decreases as \( B_|| \) increases. Electron-spin-resonance measurements demonstrate that the spin-orbit interactions are very small in the present system. An in-plane magnetic field can modify the wave function in the confinement direction and cause a distortion of the 2D Fermi lines. However, this effect increases \( B_{\text{CR}} \). The enhancement of the cyclotron mass is estimated to be only about 1% for 7 T in the present 2DES.

In summary, we have performed the cyclotron resonance measurements on a high-mobility Si 2DES in the presence of an in-plane magnetic field \( B_|| \). The relaxation time \( \tau_{\text{CR}} \), obtained from the linewidth, was found to have a negative \( B_|| \) dependence, which is similar to that of the transport scattering time \( \tau_e \). The resonance peak shifts unexpectedly toward lower \( B_\perp \) as \( B_|| \) increases.

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References

1. E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys. 73, 251 (2001).
2. S. Das Sarma, and E. H. Hwang, Solid State Commun. 135, 579 (2005).
3. B. Spivak, S. V. Kravchenko, S. A. Kivelson, X. P. A. Gao, Rev. Mod. Phys. 82, 1743 (2010).
4. E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).
5. D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. 79, 2304 (1997).
6. T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, Phys. Rev. Lett. 82, 3875 (1999).
7. T. Okamoto, K. Hosoya, S. Kawaji, A. Yagi, A. Yutani, and Y. Shiraki, Physica (Amsterdam) 6E, 260 (2000).
8. T. Okamoto, M. Ooya, K. Hosoya, and S. Kawaji Phys. Rev. B 69, 041202(R) (2004).
9. K. Lai, W. Pan, D. C. Tsui, S. A. Lyon, M. M{"u}hlberger, and P. Sch{"a}ffler, Phys. Rev. B 72, 081313(R) (2005).
10. J. Yoon, C. C. Li, D. Shahar, D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. 84, 4421 (2000).
11. E. Tutuc, E. P. De Poortere, S. J. Papadakis, and M. Shayegan, Phys. Rev. Lett. 86, 2858 (2001).
12. E. Tutuc, S. Melinte, and M. Shayegan, Phys. Rev. Lett. 88, 036805 (2002).
13. J. Zhu, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. 90, 056805 (2003).
14. E. P. De Poortere, E. Tutuc, Y. P. Shkolnikov, K. Vakili, and M. Shayegan, Phys. Rev. B 66, 161308(R) (2002).
15. O. Gunawan, T. Gokmen, K. Vakili, M. Padmanabhan, E. P. De Poortere, M. Shayegan, Nature Physics 3, 388 (2007).
16. X. P. A. Gao, G. S. Boebinger, A. P. Mills, A. P. Ramirez, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 73, 241315(R) (2006).
17. I. L. Drichko, I. Yu. Smirnov, A. V. Suslov, O. A. Mironov, and D. R. Leadley, Phys. Rev. B 79, 205310 (2009).
18. R. Masutomi, K. Sasaki, I. Yasuda, A. Sekine, K. Sawano, Y. Shiraki, and T. Okamoto, Phys. Rev. Lett. 106, 196404 (2011).
19. A. Yutani and Y. Shiraki, Semicond. Sci. Technol. 11, 1009 (1996); J. Cryst. Growth 175-176, 504 (1997).
20. Assuming an energy-independent density of states, the Pauli paramagnetic spin polarization \( P \) is calculated as a function of \( B_\parallel \) and \( T \). Here we take into account the effects of electron-electron interactions on the \( g \) factor and the effective mass according to V. M. Pudalov, M. E. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. 88, 196404 (2002).
21. O. Prus, M. Reznikov, U. Sivan, and V. Pudalov, Phys. Rev. Lett. 88, 016801 (2002).
22. X. P. A. Gao, G. S. Boebinger, A. P. Mills, Jr., A. P. Ramirez, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 94, 086402 (2005).
23. K. Toyama, T. Nishioka, T. Okamoto, K. Sawano, Y. Shiraki (unpublished). From the analysis of the \( I - V \) characteristics, the relationship between \( T_e \) and the Joule heating power \( Q \) was found to be \( Q \propto T_e^5 - T_o^5 \) in the temperature range from 0.6 K to 8 K.
24. J. Matsunami, M. Ooya, and T. Okamoto, Phys. Rev. Lett. 97, 066602 (2006).
25. L. Smrčka and T. Jungwirth, J. Phys. Condens. Matter 16, 55 (1994).
26. Due to a one-side doping and applied gate voltage, the confining potential is regarded as a triangular well rather than a square well. The average distance of electrons from the interface is calculated to be 4 nm which is smaller than the magnetic length \( l_B = (\hbar/eB)^{1/2} \) (10 nm at 7 T).