Metallic Behavior of Cyclotron Relaxation Time in Two-Dimensional Systems

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Cyclotron resonance of two-dimensional electrons is studied at low temperatures down to 0.4 K for a high-mobility Si/SiGe quantum well which exhibits a metallic temperature dependence of dc resistivity ρ. The relaxation time τ_{CR} shows a negative temperature dependence, which is similar to that of the transport scattering time τ_t obtained from ρ. The ratio $\tau_{\mathrm{CR}}/\tau_t$ at 0.4 K increases as the electron density N_s decreases, and exceeds unity when N_s approaches the critical density for the metal-insulator transition.

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The metallic behavior in two-dimensional (2D) systems has attracted much attention [1–3]. In 1994, Kravchenko *et al.* observed a strong metallic temperature dependence of the zero-magnetic-field ($B = 0$) resistivity ($d\rho/dT > 0$) of high-mobility 2D electron systems (2DESs) in Si metal-oxide-semiconductor field-effect transistors (Si-MOSFETs), and a metal-insulator transition (MIT) by changing the electron density N_s [4,5]. According to the scaling theory of localization [6], which neglects electron-electron (e-e) interactions, there can be no metallic state in 2D at $B = 0$ and the system should become an insulator in the zero-temperature limit. Thus the observation of the 2D metallic behavior and the MIT has caused much controversy and is still a widely debated subject [1–3]. Recently, theoretical calculations using the renormalization group equations suggest that the metallic phase is stabilized by e-e interactions even at $T = 0$ [7]. Because the experimental data on Si-MOSFETs are in agreement with this theory, Anissimova *et al.* argue that the 2D MIT is an interaction driven and N_s-tuned quantum phase transition (QPT) [8]. From another point of view, $\rho(T)$ was calculated using the finite temperature Drude-Boltzmann theory by Das Sarma and Hwang [2,9,10]. The experimental data were quantitatively reproduced for different 2D systems by taking into account the temperature dependent screening of residual impurities. An entirely different explanation was given by Spivak and Kivelson, who introduced random microemulsion phases between a Fermi liquid and a Wigner crystal (WC) phase [3,11]. The reduction of ρ with decreasing temperature was explained in terms of a decrease in the WC fraction having higher spin entropy.

The metallic temperature dependence of ρ has been observed for various low-density 2D electron and hole systems, such as Si-MOSFETs [4], p-SiGe quantum wells (QWs) [12,13], p-GaAs/AlGaAs heterojunctions [14,15], n-AlAs QWs [16], n-GaAs/AlGaAs heterojunctions [17,18] and n-Si QWs [19,20]. A common feature of these systems is a strong e-e interaction, which is characterized by the Wigner-Seitz radius $r_s \equiv (\pi N_s)^{-1/2}/a_B = \pi^{1/2}(e/h)^2(m^*/\kappa\epsilon_0)N_s^{-1/2}$. Here a_B is the effective Bohr radius, m^* is the effective mass, and κ is the dielectric constant. It is also suggested that the spin and/or valley degeneracies play an important role in the appearance of the metallic behavior [19,21,22].

According to the Drude formula, the $B = 0$ dc resistivity is related to the transport scattering time τ_t as $\rho^{-1} = e^2 N_s \tau_t/m^*$. Since τ_t is not sensitive to small-angle scattering events, it is not identical to the single-particle relaxation time τ_s [23]. If $W_{k,k'}$ is proportional to the probability of scattering from state k to k' and θ is the scattering angle, τ_t and τ_s are given by

$$\frac{1}{\tau_t} = \int W_{k,k'}(1 - \cos\theta)dk', \tag{1}$$

$$\frac{1}{\tau_s} = \int W_{k,k'}dk'. \tag{2}$$

It is believed that the ratio is large ($\tau_t/\tau_s \gg 1$) for long-range scattering potentials and small ($\tau_t/\tau_s \approx 1$) for short-range scattering potentials. Experimentally, the single-particle relaxation time have been deduced from the magnitude of the Shubnikov–de Haas oscillations (τ_{SdH}) [24,25] and from the cyclotron resonance (τ_{CR}) [26,27]. The ratio $\tau_t/\tau_{\mathrm{SdH}}$ was measured for various semiconductor 2D systems in order to identify the main low-temperature scattering mechanisms. However, it has been pointed out that τ_{SdH} is severely affected by density inhomogeneities especially in high-mobility samples [27]. In contrast, τ_{CR} is thought to be insensitive to density inhomogeneities. Furthermore, τ_{CR} can be measured even at high temperatures where the Shubnikov–de Haas oscillations disappear.

We study τ_{CR} in a high-mobility Si 2DES which exhibits the metallic T-dependence of ρ. For N_s between 0.74 and 1.93×10^{15} m^{-2}, τ_{CR} monotonically increases with

decreasing temperature in the range from 7 K to 0.4 K. The overall behavior of the T dependence of τ_{CR} is similar to that of τ_t. The ratio τ_{CR}/τ_t at 0.4 K increases with decreasing N_s, and τ_{CR} becomes larger than τ_t in the region near the MIT.

We used a Si/SiGe heterostructure with a 20-nm-thick strained Si QW sandwiched between relaxed $Si_{0.8}Ge_{0.2}$ layers [28]. The electrons are provided by a Sb-δ-doped layer 20 nm above the channel and N_s can be controlled by varying bias voltage V_{BG} of a p-type Si(001) substrate 2.1 μm below the channel at 20 K. The 2DES has a high-mobility of 49 $m^2/V\,s$ at $N_s = 2.36 \times 10^{15}$ m^{-2} ($V_{BG} = 0$ V) and $T = 0.4$ K. Although the sample was mounted in a pumped ^{3}He refrigerator, a thermal insulation system enabled us to vary the sample temperature up to 10 K on the condition that the base temperature of the carbon bolometer was kept constant at 0.35 K. The schematic drawing of the equipment is described elsewhere [29]. The cyclotron resonance (CR) measurements were performed using 100 GHz millimeter-wave radiation. The radiation power was kept low enough so that electron heating effects can be neglected. In order to measure ρ and N_s, the sample was fabricated in Hall bar geometry and Ohmic contacts were made outside the irradiation area.

Figure 1 shows T dependence of ρ at $B = 0$ for different N_s. The dashed curves are obtained by subtracting the contribution of phonon scattering [30] from the experimental data. The Fermi temperature T_F is indicated by black arrows. Clear metallic T dependence of ρ can be seen in the range $T \lesssim 0.3T_F$ for $N_s > 0.5 \times 10^{15}$ m^{-2}, while it disappears for $N_s < 0.5 \times 10^{15}$ m^{-2}. The value of r_s ranges from 7.5 to 5.0 for $(0.55–1.22) \times 10^{15}$ m^{-2}, indicating strong electron correlation in this system. Furthermore the valley degeneracy of $g_v = 2$ in Si 2DESs, as well as the spin degeneracy of $g_s = 2$, reduces

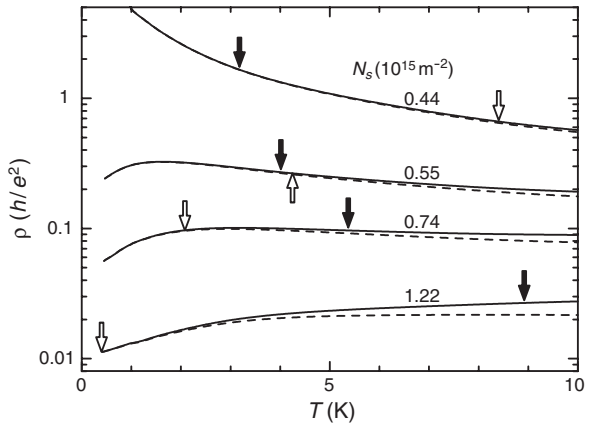

FIG. 1. Temperature dependence of resistivity at $B = 0$ for different electron densities. The solid curves are the experimental data. The dashed curves are obtained by subtracting the contribution of phonon-scattering assuming Matthiessen's rule. The black arrows indicate the Fermi temperature and the white arrows indicate $T = \hbar/k_B\tau_t$.

the Fermi energy ($\varepsilon_F = 2\pi\hbar^2 N_s/g_v g_v m^*$) and leads to the enhancement of the relative strength of the e-e interaction. The white arrows indicate the temperature at which the scattering rate τ_t^{-1} is equal to $k_B T/\hbar$. Here, τ_t is related to the $B = 0$ dc resistivity as $\tau_t = m^*/e^2 N_s \rho$. The metallic behavior can be observed both for $k_B T < \hbar\tau_t^{-1}$ (low-N_s), where electrons propagate diffusively, and for $k_B T > \hbar\tau_t^{-1}$ (high-N_s), referred to as the ballistic regime [31].

Figure 2(a) shows typical CR observed at $N_s = 1.51 \times 10^{15}$ m^{-2} for different temperatures. From the half-width at half maximum ΔB, τ_{CR} is obtained as $\tau_{CR} = B_{CR}/(\omega \Delta B)$. Here B_{CR} is the resonance magnetic field and ω is the microwave frequency

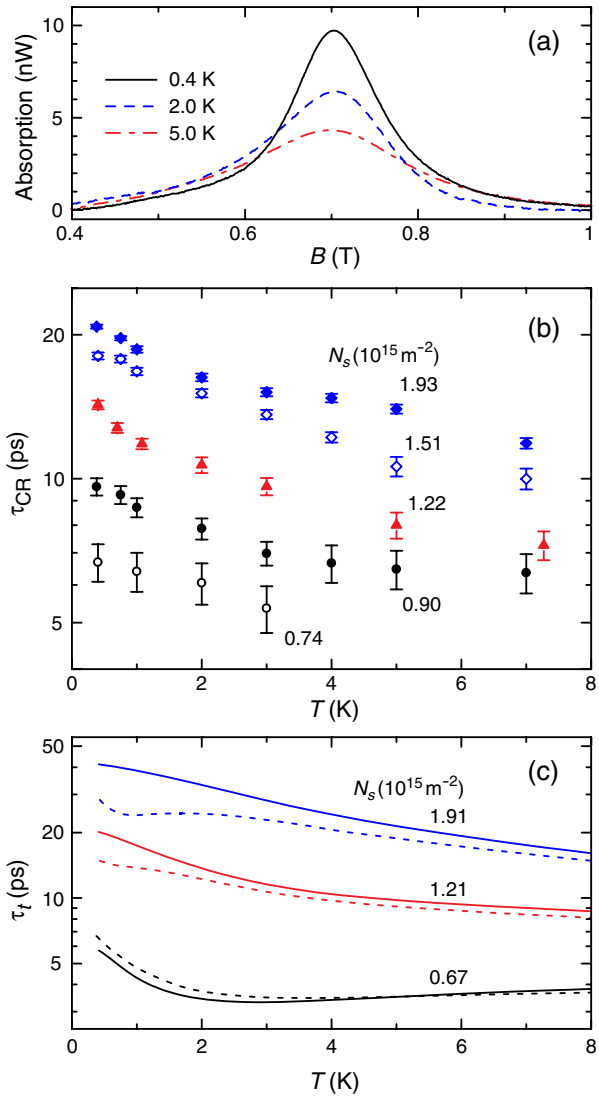

FIG. 2 (color online). (a) CR traces at $N_s = 1.51 \times 10^{15}$ m^{-2} for $T = 0.4$, 2.0 and 5.0 K. (b) T dependence of τ_{CR} for $N_s = 1.93$, 1.51, 1.22, 0.90, 0.74×10^{15} m^{-2} (from top to bottom). (c) Solid curves are T dependence of τ_t for $N_s = 1.91$, 1.21, 0.67×10^{15} m^{-2} (from top to bottom). The scattering time obtained from the longitudinal resistivity at $B = B_{CR}$ is also plotted (dotted curves).

($\omega/2\pi = 100$ GHz). In Fig. 2(b), τ_{CR} is plotted as a function of T for different N_s. In the wide density range, τ_{CR} is metallic, i.e., it increases with decreasing temperature. For comparison, τ_t determined from the $B = 0$ dc resistivity is shown in Fig. 2(c) (solid curves). The T dependence of τ_{CR} is similar to that of τ_t. In order to study the effect of the magnetic field on the transport scattering time, we have measured the longitudinal resistivity ρ_{xx} at $B = B_{CR}$. According to the classical Drude picture, the scattering time $\tau_b = m^*/e^2 N_s \rho_{xx}$ is obtained as a function of T and shown in Fig. 2(c) as the dotted curves. Except in the low-T region for high N_s where the Shubnikov–de Haas oscillations are superimposed, the deviation of $\tau_b(T)$ from $\tau_t(T)$ is small. This demonstrates that the magnetic field applied for the CR measurements is small enough not to affect the transport scattering time significantly.

The results shown in Fig. 2 indicate that the scattering time has the metallic T-dependence over a very wide frequency range from dc to 100 GHz. At 100 GHz, a characteristic length $l_\omega = v_F/\omega$ becomes much shorter ($l_\omega = 50$–70 nm) than the electron mean free path $\lambda = 120$–1900 nm, where v_F is the Fermi velocity. Furthermore, the photon energy $\hbar\omega = 4.8$ K exceeds the typical temperatures where the metallic behavior is observed clearly. At this stage, it is unclear why the metallic T dependence of the scattering time occurs under very different conditions. However, we believe that our observations will provide a strong constraint on theoretical models.

In order to discuss the 2D metallic behavior further, it is important to identify the type of disorder potential. In Figs. 3(a) and 3(b), τ_{CR}, τ_t and τ_{CR}/τ_t at $T = 0.4$ K are shown as a function of N_s. For high N_s between 1 and 2×10^{15} m^{-2}, τ_{CR} is smaller than but comparable to τ_t. This suggests that short-range potential fluctuations which lead to large-angle scattering play a dominant role in the metallic regime, although the Si/SiGe 2DES studied is a high-mobility modulation-doped heterostructure. This is consistent with the recent work of Clarke *et al.* who compared the strength of the metallic behavior in GaAs 2D hole systems dominated by long- and short-range disorder [32].

As N_s decreases and approaches the critical density for the MIT, τ_t rapidly decreases as shown in Fig. 3(a). On the other hand, the N_s-dependence of τ_{CR} seems to be gradual, although we were not able to determine it for $N_s < 0.5 \times 10^{15}$ m^{-2} due to the broadening of the CR signal. The ratio τ_{CR}/τ_t at $T = 0.4$ K exceeds unity near the MIT as shown in Fig. 3(b). This cannot be understood in a single-particle picture on which Eqs. (1) and (2) is based. In Fig. 3(c), B_{CR} and the corresponding effective mass $m_{CR} = eB_{CR}/\omega$ are shown as a function of N_s. While B_{CR} is independent of N_s and m_{CR} is close to $m^* = 0.19m_e$ at $T = 3.0$ K, B_{CR} increases rapidly with decreasing N_s

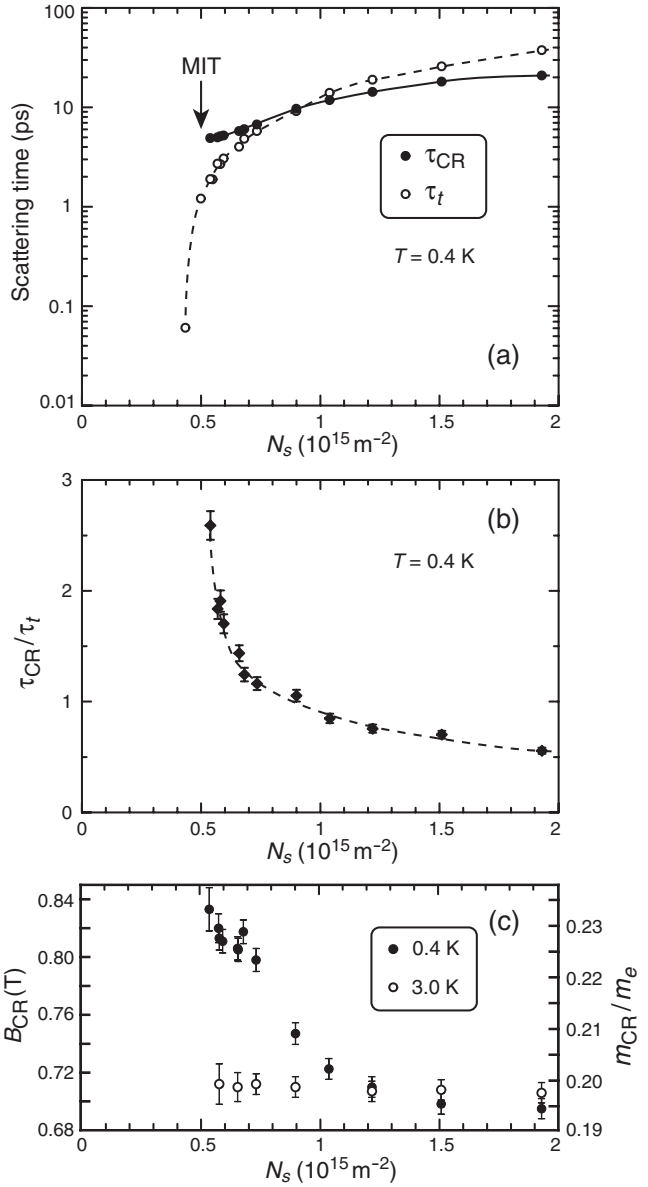

FIG. 3. (a) Density dependence of τ_{CR} (solid circle) and τ_t (open circle) at 0.4 K. The arrow indicates the critical density for the MIT determined from the T dependence of τ_t. Solid and dashed lines are a guide to the eye. (b) The ratio of τ_{CR} to τ_t at 0.4 K. (c) The resonance magnetic field B_{CR} and the corresponding effective mass m_{CR} at 0.4 K (solid circle) and 3.0 K (open circle).

near the MIT at $T = 0.4$ K. In Ref. [33], a narrowing of the CR absorption line, together with a deviation of the resonance frequency from $\omega_c = eB/m^*$, has been reported for a Si-MOSFET in the extreme quantum limit. The observed width is about 5 times narrower than that expected from τ_t. The results were explained in terms of the formation of a magnetic-field-induced Wigner glass (WG). Even at $B = 0$, a pinned WC or WG is expected to be formed in low-density 2D semiconductor systems. Pudalov *et al.* observed nonlinear dc conduction with a sharp threshold

electric field in the insulating regime of Si-MOSFETs and attributed it to that of a pinned WC [34]. Chui and Tanatar found from their Monte Carlo studies that the WC can be stabilized at $r_s = 7.5$ in the presence of a very small amount of disorder [35]. Our results for low N_s imply that electron correlation effects are important even in the metallic region at low temperatures.

In summary, we have performed the cyclotron resonance measurements on a high-mobility Si 2DES. The relaxation time τ_{CR}, obtained from the linewidth, was found to have a negative T dependence, which is similar to that of τ_t corresponding to the metallic dc resistivity. In the region around the MIT, τ_{CR} exceeds τ_t and B_{CR} becomes larger than $m^*\omega/e$. These unexpected behaviors cannot be described as a noninteracting electron system. Further theoretical calculations taking into account cyclotron resonance in the metallic phase are eagerly desired.

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