

Temperature, electron density and in-plane magnetic field dependence of cyclotron relaxation time in the two-dimensional metallic phase

R. Masutomi¹, T. Chiba¹, K. Sasaki¹, I. Yasuda¹, A. Sekine¹, K. Sawano², Y. Shiraki² and T. Okamoto¹

¹Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

²Research Center for Silicon Nano-Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan

E-mail: masutomi@phys.s.u-tokyo.ac.jp

Abstract. We have performed cyclotron resonance measurements on two-dimensional electrons in the metallic phase. The temperature, electron density and in-plane magnetic field dependence of cyclotron and transport scattering time are reported for a high-mobility Si/SiGe quantum well.

1. Introduction

The metallic temperature (T) dependence of resistivity (ρ) has been observed in various two-dimensional (2D) systems [1, 2, 3]. A common feature of these systems is a strong electron-electron (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 N_s is the electron density, a_B is the effective Bohr radius, m^* is the effective mass and κ is the dielectric constant. According to the scaling theory of localization, which neglects e - e interactions, there can be no metallic state in 2D at a zero magnetic field and the system should become an insulator in the zero-temperature limit [4]. Thus the observation of the 2D metallic behavior and the metal-insulator transition (MIT) has caused much controversy and is still a widely debated subject. It is also suggested that the spin and/or valley degeneracies play an important role in the appearance of the metallic behavior [5, 6].

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 [7]. 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

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

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

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}) [8, 9] and from the cyclotron resonance (τ_{CR}) [10, 11]. The ratio τ_t/τ_{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 [11]. 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. In this paper, we report the temperature, electron density [12] and in-plane magnetic field dependence [13] of τ_{CR} and τ_t in the 2D metallic phase.

2. Experiment

We used a *n*-Si/SiGe heterostructure with a 20-nm-thick strained Si channel sandwiched between relaxed $\text{Si}_{0.8}\text{Ge}_{0.2}$ layers [14]. The electrons are provided by a Sb- δ -doped layer 20 nm above the channel. We can control N_s by varying bias voltage V_{BG} of a *p*-type Si(001) substrate 2.1 μm below the channel at 20 K. The 2D electron system (2DES) has a high mobility of 49 $\text{m}^2/\text{V s}$ at $N_s = 2.36 \times 10^{15} \text{ m}^{-2}$ ($V_{\text{BG}} = 0 \text{ V}$) and $T = 0.4 \text{ K}$. The use of the extremely high-mobility sample allows us to probe low N_s region, where the Coulomb interaction between electrons is sufficiently larger than the Fermi energy.

Although the sample was mounted in a pumped ^3He 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 [15, 16]. 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. For the measurement of in-plane magnetic field $B_{\parallel}$ dependence, we took electron heating effect in the 2DES under excitation at 100 GHz [13]. A two-axis vector magnet system was used to apply an in-plane magnetic field $B_{\parallel}$ and a perpendicular magnetic field $B_{\perp}$ for CR measurements.

3. Results and discussion

Fig. 1 shows T -dependence of ρ at 0 T (solid line) for different N_s without millimeter-wave radiation. Clear metallic T -dependence of ρ can be seen for $N_s > 0.5 \times 10^{15} \text{ m}^{-2}$, while it disappears for $N_s < 0.5 \times 10^{15} \text{ m}^{-2}$. In order to study the effect of the magnetic field on the transport property, we also plotted the longitudinal resistivity ρ_{xx} at 0.7 T ($\sim B_{\text{CR}}$) in Fig. 1 (dash line), where B_{CR} is the resonance magnetic field. The deviation of $\rho_{xx}(T)$ at 0.7 T from $\rho(T)$ at 0 T is small. This indicates that the magnetic field applied for the CR measurements is small enough not to affect the transport property significantly.

Fig. 2 shows T -dependence of τ_{CR} for different N_s . From the half-width at half maximum ΔB of a CR curve, τ_{CR} is obtained as $\tau_{\text{CR}} = B_{\text{CR}}/(\omega\Delta B)$. Here ω is the microwave frequency ($\omega/2\pi = 100 \text{ GHz}$). At all N_s , τ_{CR} is metallic, i.e., it increases with decreasing T . This result indicates that the metallic T -dependence of the scattering time is shown over a wide frequency range from dc to 100 GHz. At 100 GHz, a characteristic length $l_{\omega} = v_F/\omega$ becomes much shorter ($l_{\omega} = 50 \sim 70 \text{ nm}$) than the electron mean free path $\lambda = 120 \sim 1900 \text{ nm}$, where v_F is the Fermi velocity. Furthermore, the photon energy $\hbar\omega = 4.8 \text{ K}$ 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 Fig. 3, τ_{CR} and τ_t at 0.4 K are plotted as a function of N_s . In order to discuss the 2D metallic behavior further, it is important to identify the type of disorder potential. For high N_s between 1 and $2 \times 10^{15} \text{ m}^{-2}$, 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

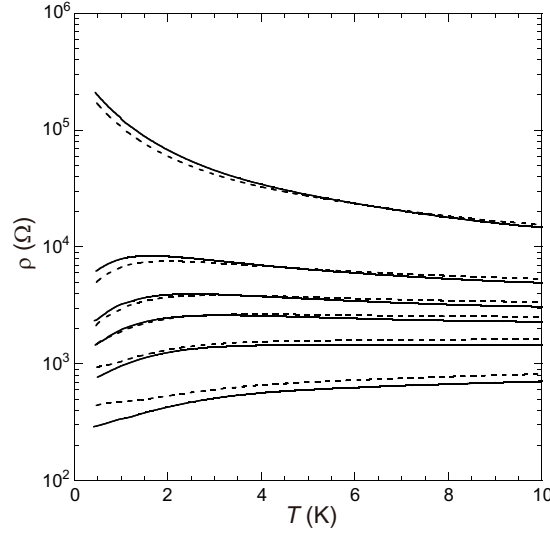


Figure 1. Temperature dependence of ρ at $B = 0$ T (solid line) and 0.7 T (dash line). The electron density is 0.44, 0.55, 0.66, 0.74, 0.90, and $1.22 \times 10^{15} \text{ m}^{-2}$ (from top to bottom).

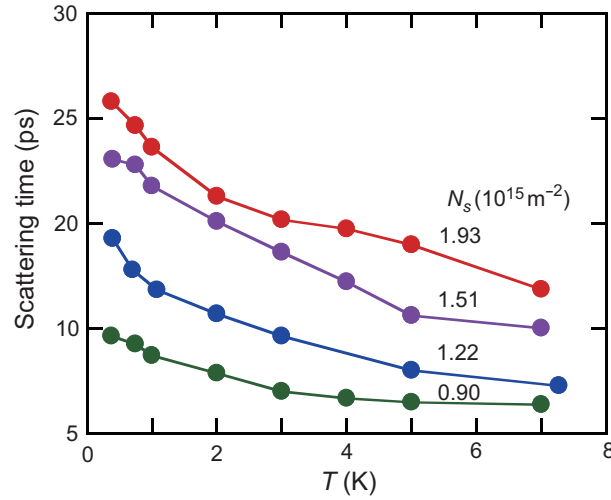


Figure 2. Temperature dependence of τ_{CR} for $N_s = 1.93, 1.51, 1.22, 0.90 \times 10^{15} \text{ m}^{-2}$.

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 [17].

As N_s approaches the critical density for the MIT, τ_t rapidly decreases, where τ_t is determined from $\tau_t = m^*/e^2 N_s \rho$ with the effective mass $m^* = 0.19m_e$. In contrast, the N_s -dependence of τ_{CR} seems to be gradual. Moreover, the ratio τ_{CR}/τ_t exceeds unity near the MIT. This cannot be understood in a single-particle picture on which Eqs. (1) and (2) is based. Our results for low N_s imply that electron correlation effects are important even in the metallic region at low

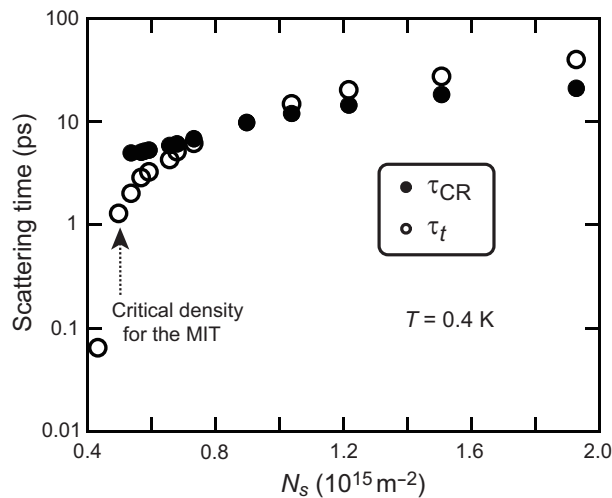


Figure 3. Electron density dependence of τ_{CR} and τ_t at 0.4 K.

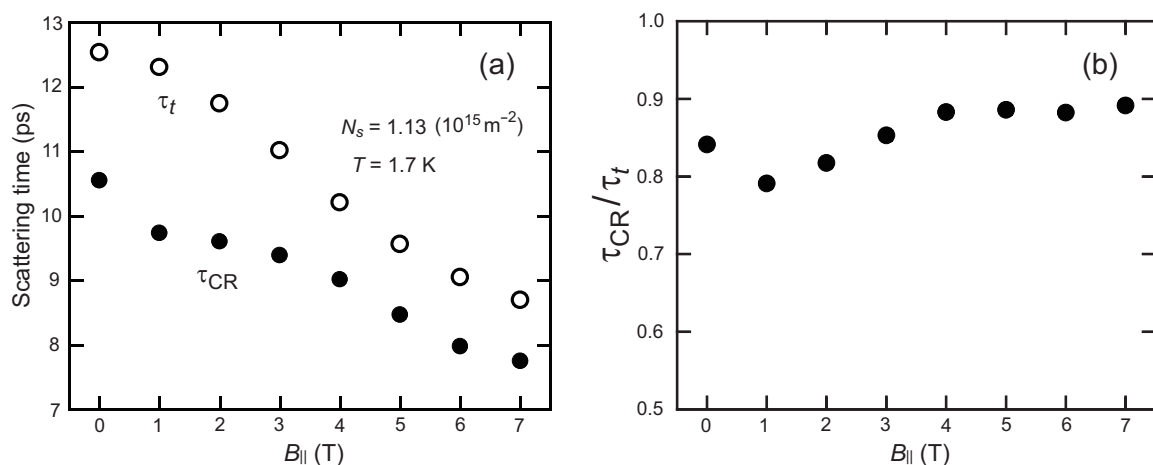


Figure 4. In-plane magnetic field dependence of (a) τ_{CR} , τ_t and (b) τ_{CR}/τ_t .

temperatures.

Fig. 4(a) shows $B_{\parallel}$ -dependence of τ_{CR} and τ_t at $T = 1.7$ K and $N_s = 1.13 \times 10^{15} \text{ m}^{-2}$. The critical magnetic field for the full spin polarization at $T = 0$ K is estimated to be 5.0 T at this density. The T -dependence of ρ exhibits apparent metallic behavior below $B_{\parallel} = 7$ T [18, 19]. The cyclotron relaxation time τ_{CR} have a negative $B_{\parallel}$ dependence, which is similar to that of τ_t . Fig. 4(b) shows τ_{CR}/τ_t as a function of $B_{\parallel}$. The ratio τ_{CR}/τ_t is close to unity, which suggests that short-range potential fluctuations which lead to large-angle scattering play a dominant role even in in-plane magnetic fields. In our measurements, B_{CR} shows an unexpected negative shift ($\sim 10\%$) with increasing $B_{\parallel}$ up to 7 T. An in-plane magnetic field can modify the wave function in the confinement direction [20]. However this effect increases B_{CR} . Further measurements are needed to clarify this behavior.

Acknowledgments

This work has partly supported by Grant-in-Aid for Young Scientists (B) (No. 23740233) and Grant-in-Aid for Scientific Research (A) (No. 21244047) from MEXT, Japan.

- [1] E. Abrahams, S. V. Kravchrenko, 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. Kravchrenko, 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] T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, *Phys. Rev. Lett.* **82**, 3875 (1999).
- [6] O. Gunawan, T. Gokmen, K. Vakili, M. Padmanabhan, E. P. DE Poortere, and M. Shayegan, *Nat. Phys.* **3**, 388 (2007).
- [7] S. Das Sarma and F. Stern, *Phys. Rev. B* **32**, 8442 (1985).
- [8] J. P. Harrang, R. J. Higgins, R. K. Goodall, P. R. Jay, M. Laviron, and P. Delescluse, *Phys. Rev. B* **32**, 8126 (1985).
- [9] P. T. Coleridge, *Phys. Rev. B* **44**, 3793 (1991).
- [10] H. Linke, P. Omling, P. Ramvall, B. K. Meyer, M. Drechsler, C. Wetzel, R. Rudeloff, and F. Scholz, *J. Appl. Phys.* **73**, 7533 (1993).
- [11] S. Syed, M. J. Manfra, Y. J. Wang, R. J. Molnar, and H. L. Stormer, *Appl. Phys. Lett.* **84**, 1507 (2004).
- [12] R. Masutomi, K. Sasaki, I. Yasuda, A. Sekine, K. Sawano, Y. Shiraki, and T. Okamoto, *Phys. Rev. Lett.* **106**, 196404 (2011).
- [13] T. Chiba, R. Masutomi, K. Sawano, Y. Shiraki, and T. Okamoto, *Phys. Rev. B* **86**, 045310 (2012).
- [14] A. Yutani and Y. Shiraki, *Semicond. Sci. Technol.* **11**, 1009 (1996); *J. Cryst. Growth* **175/176**, 504 (1997).
- [15] R. Masutomi, A. Sekine, K. Sasaki, K. Sawano, Y. Shiraki, and T. Okamoto, *Physica E* **42**, 1184 (2010).
- [16] R. Masutomi, K. Sasaki, I. Yasuda, A. Sekine, K. Sawano, Y. Shiraki, and T. Okamoto, *Journal of Physics: Conference Series* **334**, 012057 (2011).
- [17] W. R. Clarke, C. E. Yasin, A. R. Hamilton, A. P. Micolich, M. Y. Simmons, K. Muraki, Y. Hirayama, M. Pepper, and D. A. Ritchie, *Nat. Phys.* **4**, 55 (2008).
- [18] T. Okamoto, K. Hosoya, S. Kawaji, A. Yagi, A. Yutani, and Y. Shiraki, *Physica* **6E**, 260 (2000).
- [19] T. Okamoto, M. Ooya, K. Hosoya, and S. Kawaji, *Phys. Rev. B* **69**, 041202(R) (2004).
- [20] L. Smröcka and T. Jungwirth, *J. Phys.: Condens. Matter* **6**, 55 (1994); **7**, 3721 (1995).