Solid State Communications 156 (2013) 45–48

Contents lists available at SciVerse ScienceDirect

Solid State Communications

journal homepage: www.elsevier.com/locate/ssc

Probing the coexistence of semiclassical transport and localization in a two-dimensional electron gas using microwave radiation

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ARTICLE INFO

Article history:
Received 14 August 2012
Accepted 26 November 2012
by M. Wang
Available online 4 December 2012

Keywords:
A. Semiconductors
A. Quantum well

ABSTRACT

We have performed magnetoresistance measurements on a GaAs/AlGaAs two-dimensional electron gas under microwave heating. Both the magneto-oscillations and magnetoresistance minima are used as electron thermometers to determine the electron effective temperature T_e. When there is no clear cyclotron gap, it is found that T_e determined from these two methods can be substantially different such that we can still distinguish localized electrons from the semiclassical conducting ones. The almost constant T_e obtained from the magnetoresistance minima reveals the survived equivalence between different Landau-band tails under insufficient localization.

1. Introduction

When a magnetic field is applied perpendicular to the plane of a two-dimensional electron gas (2DEG), Landau quantization effect modulates the 2D density of states. At low magnetic fields, the longitudinal resistance R_{xx} follows the Shubnikov–de Haas (SdH) formalism given by [1–3]

$$R_{xx} \approx R_0 + F(B)\frac{\chi}{\sinh\chi}\cos(\pi(\nu+1)), \tag{1}$$

under such quantization effect when quantum localization is negligible. Here $F(B)=4R_0c\exp[-\pi/\mu_qB]$, $\chi=4\pi^3k_Bm^*T/heB$, ν, k_B, e, h, m^*, T, μ_q, B, R_o, and c are the filling factor, Boltzmann constant, electron charge, Plank constant, electron effective mass, temperature, quantum mobility, magnetic field, the resistance at $B=0$, and a constant close to unity, respectively. According to Eq. (1), at a specific B the function $f(m^*,T)\equiv\ln(\Delta R_{xx}/T)+\ln(1-e^{-2\chi})$ satisfies

$$f(m^*,T)=f_0-\frac{4\pi^3k_Bm^*}{heB}T, \tag{2}$$

where $f_0\sim \text{const}+\ln(4\pi^3k_Bm^*/heB)-(\pi/\mu_q)1/B$ is a function of B. Here ΔR_{xx} denotes the amplitude of SdH oscillations and equals $F(B)\times\chi/\sinh\chi$ according to Eq. (1). On the other hand, at sufficiently high magnetic fields when quantum localization effects become important, an exponential T-dependence of the magnetoresistance minimum $R_{xx,min}$ is given by [4,5]

$$R_{xx,min}\approx R_{xx}(0)\exp\left[\frac{-\Delta E}{2k_BT}\right], \tag{3}$$

over a suitable temperature range. Here ΔE which can be obtained from the slope of $\ln R_{xx,min}-1/T$, is the activation energy and is expected to be close to the cyclotron gap. In this case, the 2DEG shows activated behaviour. That is, electrons are thermally activated from the localized states at Landau-band tails to the extended states near the centers of the Landau-bands.

Since the SdH formula is derived semiclassically with no localization effect whereas activated behaviour requires the existence of quantum localization, at first glance, SdH oscillations and activated behaviour do not normally co-exist. However, it has been reported that cyclotron gap indicated by the activated behavior can be identified when ΔR_{xx} follows the SdH formula [6]. Two types of electrons are considered to explain this coexistence. One type responsible for $R_{xx,min}$ is composed of the localized electrons at Landau-band tails whereas the other type responsible for ΔR_{xx} consists of the semiclassical conducting electrons near Landau-band centers. But more studies are necessary to clarify whether localization can coexist with the semiclassical conducting behavior. It was reported in Ref. [7] that there is no localization-induced hopping under Eq. (1), which can become invalid with increasing B before quantum localization induces the integer quantum Hall effect [8]. On the other hand, Eq. (3) is used to investigate the activated transport only in an intermediate temperature range because deviation from Eq. (3) is expected at

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http://dx.doi.org/10.1016/j.ssc.2012.11.019

either low [7] or high temperatures. It is possible that there is no localization, but experimental data can be well fitted to Eq. (2) over a small temperature range. Therefore, more studies are necessary to clarify whether quantum localization can coexist with the semiclassical SdH formula.

In addition to zero resistance state [9,10] and nonlinear magnetoresistance oscillations [11], microwave radiation may introduce electron heating and/or dephasing in semiconductors. Therefore, it is interesting to further study the coexistence of activated behaviour and the SdH formula under microwave radiation. In this communication, we use both damping of SdH oscillations and activated behaviour at SdH minima as independent electron thermometers. When an electron system is heated appreciably by microwave radiation, the equilibrium between the electrons and phonons can be broken. In this case, the electron temperature T_e can be substantially higher than the crystal lattice temperature T_l [12]. Various physical phenomena, such as SdH oscillations [13], weak localization correction [14], single electron tunneling [15], thermopower of a one-dimensional constriction [16], and magneoresistance [17] have been applied as electron thermometers. Using both ΔR_{xx} and $R_{xx,min}$ as thermometers under the microwave radiation when Eq. (2) remains valid, different electron temperatures $T_{e,SdH}$ and $T_{e,min}$ are obtained from ΔR_{xx} and $R_{xx,min}$ although the value of ΔE obtained from Eq. (3) is much smaller than the cyclotron gap. The existence of the two electron temperatures shows that $R_{xx,min}$ and ΔR_{xx} are not dominated by the same type of electrons although the small ΔE and the validity of the SdH formula indicate the weak strength of localization.

2. Experimental

The sample which we studied is an AlGaAs/GaAs heterostructure LM4882. The following layer sequence was grown on a GaAs semi-insulating substrate: 1 μm undoped GaAs, 20 nm undoped $Al_{0.33}Ga_{0.67}As$, 40 nm Si doped (2×10^{18} cm^{-3}) $Al_{0.33}Ga_{0.67}As$, and a 10 nm undoped GaAs cap layer. Indium was alloyed near the sample edges and was annealed at 450 °C in vacuum. Magneto-transport measurements have been performed by a standard low-frequency ac technique with a current injection of 1 μA. Magnetic field was applied normal to the 2DEG plane and the sample temperature was maintained between 1.4 K and 4.2 K. For the microwave measurements, linearly polarized microwave (MW) irradiation from a "carcinotron" tunable in the 33–50 GHz frequency range was employed. Similar results were obtained at different frequencies and in this paper, data obtained using a frequency of 42.04 GHz will be presented. To provide minimal damping of the MW power, a circular (internal diameter of 10 mm) waveguide to rectangular window WR 22 (5.8 mm× 2.6 mm) with a reduction brass piece of 5 cm in length was used to obtain output linear polarization of microwave across the WR 22 windows. MW power was attenuated using a diode attenuator placed at the output of the carcinotron. The sample was placed at a distance of 1–2 mm in front of the waveguide output in a variable temperature cryostat. The sample temperature was monitored using a Allen Bradley resistor mounted close to the sample.

3. Results and discussion

The inset to Fig. 1 shows the magneoresistance measurements $R_{xx}(B)$ with no microwave radiation at various temperatures. With increasing temperature, damping of the magnetoresistance oscillations is observed. In order to further study the observed oscillations, we investigate the T-dependence of the amplitudes

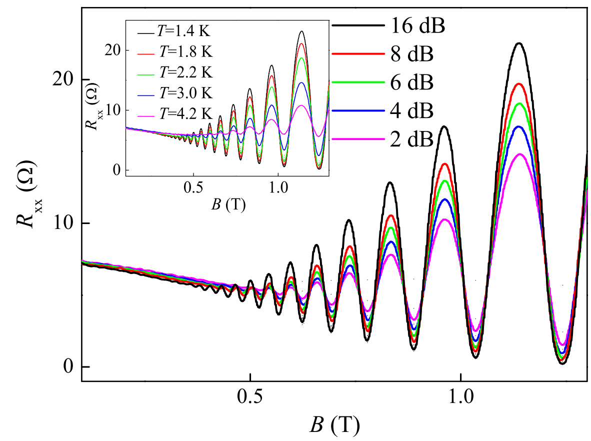

Fig. 1. (Color online) The four-terminal resistance measurements $R_{xx}(B)$ at different microwave attenuations when the temperature $T=1.4$ K. The inset shows the four-terminal resistance measurements $R_{xx}(B)$ without microwave at various temperatures.

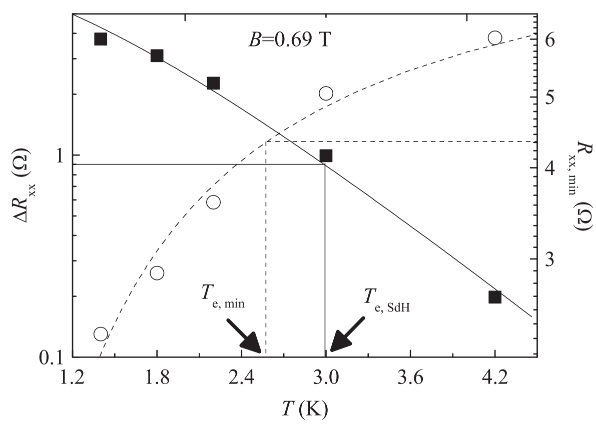

Fig. 2. The left (right) panel shows the SdH amplitudes (magetoresistance minima) versus temperature T at $B=0.69$ T on a semi-logarithmic scale. The solid (open) circles correspond to the data points to determine the fitting curve illustrated by the solid (dash) line. The solid (dashed) horizontal line corresponds to the amplitude (minima) under the continuous microwave radiation of 2 dB power for $T=1.4$ K. The vertical line indicates the temperature 3 K. $T_{e,min}$ and $T_{e,SdH}$ indicate the estimated electron effective temperatures determined from the resistance minimum and the amplitudes of the SdH oscillations, respectively.

ΔR_{xx} which was fitted to Eq. (2). Inserting a trial effective mass m_t^* into the function f on the left hand side of Eq. (2), as mentioned in Ref. [18], at a specific B we can obtain m_s^* from the slope $4\pi^3 k_B m^*/heB$ of $f-T$. The trial value m_t^* can be taken as the effective mass m^* at such a specific B if $|m_s^* - m_t^*| < \Delta m$, or we shall reset m_s^* as m_t^* and iterate until such an inequality is satisfied. Here Δm denotes the acceptable error. Then we can check the validity of SdH formula by the value of m^*, how good the fitting of the ΔR_{xx} to the factor $\chi/\sinh\chi$ at any B, and whether the function $f_0(B) - \ln(4\pi^3 k_B m^*/heB)$ is linear in $1/B$ or not. In this study, we set $\Delta m = 0.001 m_0$ and we obtain $m^* = (0.067 \pm 0.003) m_0$ for 0.62 T $\leq B \leq$ 1.25 T. Here m_0 is the rest mass of an electron. The values of m^* over such a magnetic-field range are reasonable for a GaAs 2D electron system, and we can see from Fig. 2 the fitting of ΔR_{xx} to the factor $\chi/\sinh\chi$ is good at $B=0.69$ T. Moreover, the fit remains good for $B = 0.62 - 1.25$ T. In addition, $f_0(B) - \ln(4\pi^3 k_B m^*/heB)$ shown in Fig. 3 is linear in $1/B$. Hence ΔR_{xx} follows the SdH formula for $B = 0.62 - 1.25$ T.

Fig. 1 shows the magneoresistance measurements $R_{xx}(B)$ at continuous microwave radiation as the sample is maintained at $T=1.4$ K. With decreasing microwave power attenuation (increasing

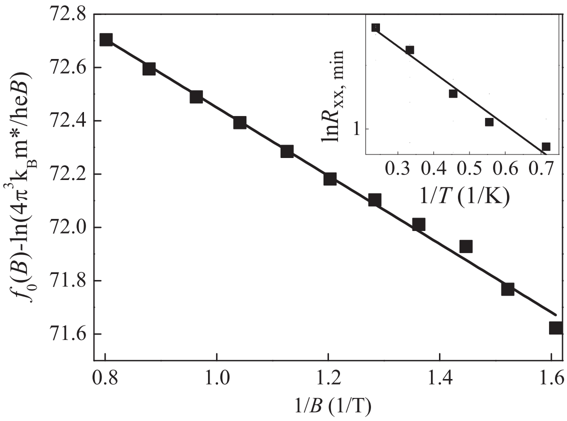

Fig. 3. The curve of $f_0(B)-\ln(4\pi^3 k_B m^*/heB)$ versus $1/B$ for $B=0.62$–1.25 T. The inset shows the fitting $\ln R_{xx,min}-1/T$ at $B=0.69$ T (see the text).

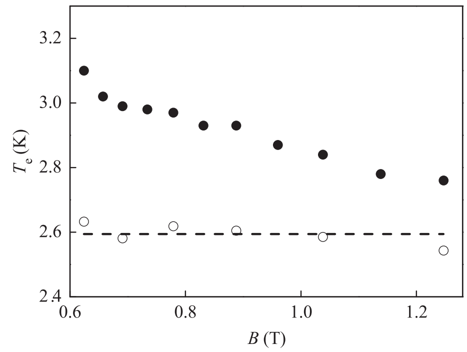

Fig. 4. The solid (open) circles represent the effective electron temperature $T_{e,SdH}$ ($T_{e,min}$) determined from SdH amplitudes (magnetoresistance minima). The horizontal dashed line is the average of $T_{e,min}$.

MW power), the amplitudes of the SdH oscillations decrease and the resistance values of SdH minima increase, which indicates electron-heating effect. The energy of the microwave is much smaller than the band-gap of GaAs therefore no electron–hole pairs are created. This is evidenced by the fact that the determined carrier density with no microwave is the same as that when the 2DEG is under continuous microwave radiation [19]. By comparing the SdH amplitudes under microwave irradiation to the T-dependence of ΔR_{xx}, we can determine the electron temperature $T_{e,SdH}$. For example, as shown in Fig. 2, at $B=0.69$ T we can determine $T_{e,SdH}=3.0$ K for the heating under the microwave power 2 dB by comparing the microwave-damped SdH amplitude, indicated by the solid horizontal line, to the fitting of R_{xx} to $\chi/\sinh\chi$.

In Fig. 2, the right panel compares the resistance minimum under the same microwave heating to the T-dependence of $R_{xx,min}$. We can see from Fig. 2 that the dashed horizontal line, which denotes the resistance minimum under the microwave heating, is away from $R_{xx,min}|_{3\ K}$ whereas the microwave-damped SdH amplitude is close to $\Delta R_{xx}|_{3\ K}$. Here $\Delta R_{xx}|_{3\ K}$ and $R_{xx,min}|_{3\ K}$ denote the SdH amplitude and resistance minima at $T=3$ K, respectively. At such a magnetic field, therefore, the electron effective temperature $T_{e,min}$ determined by $R_{xx,min}$ should be different from $T_{e,SdH}$ obtained from ΔR_{xx}. Although $\Delta E=0.35$ meV revealed by the slope of the linear fit to $\ln R_{xx,min}-1/T$, which is shown in the inset to Fig. 3 is much smaller than the cyclotron gap 1.2 meV, we can take such a fitting as an empirical curve to obtain $T_{e,min}$. We can see from the right panel of Fig. 2 that the electron temperature obtained by such an empirical way is 2.6 K and is lower than the value determined by SdH amplitude. $R_{xx,min}$ also yields lower T_e than that obtained from ΔR_{xx} as we decrease the microwave power.

We now propose a possible physical picture for the difference in the measured T_e using the two independent methods. The SdH formalism is semiclassically derived without considering high-field localization which leads to the integer quantum Hall effect. On the other hand, the localization strength oscillates with increasing B and increases quickly near the minimum points of $R_{xx}(B)$. Although the localization strength can become so weak that there is no clear cyclotron gap when the SdH formula holds true, there could still be localized effect when such strength reaches a local maxima at the minima in $R_{xx}(B)$. Therefore, the localized effect can induce the deviation of $T_{e,min}$ from $T_{e,SdH}$, for which the dominated electrons responsible for SdH amplitudes are semiclassically conducting. Since ΔE is not of the reasonable value, our study shows that the localized electrons can be distinguished from the semiclassical conducting one by microwave heating even when there is no clear cyclotron gap.

Fig. 4 compares the B-dependence of the effective temperatures determined by $R_{xx,min}$ and by ΔR_{xx} under 2 dB microwave. In Fig. 4, $T_{e,SdH}$ decreases monotonically from 3.2 K to 2.7 K as B increases from 0.62 T to 1.25 T whereas $T_{e,min}$ is approximately B-independent near 2.6 K. We note that all the Landau bands are equivalent under localization such that Landau-level addition transformation [20–22] works well at high enough B although such equivalence can become invalid as the localization strength is weak enough for the validity of SdH formula. Since $R_{xx}(B)$ reaches the minima as the Fermi energy just locates at Landau-band tails and the localization strength reaches local maxima [7,19,23,24], the almost constant $T_{e,min}$ in our study reveals the survival of the equivalence between different localized Landau-band tails when the SdH formula holds true.

4. Conclusion

In conclusion, magnetoresistance measurements are performed on a GaAs/AlGaAs two-dimensional electron gas under continuous microwave radiation. Both the SdH amplitudes and magnetoresistance minima are used as electron thermometers to determine the electron effective temperature T_e under the microwave heating. It is found that T_e determined from these two methods can be substantially different even when there is no clear cyclotron gap, which indicates the difference between electrons at Landau-band tails and those responsible for the semiclassical SdH oscillations. Therefore, localization may occur at Landau-band tails without clear cyclotron gap, under which the localized and semiclassical conducting electrons can be distinguished by the microwave heating. The effective temperature determined by the resistance minima shows that the tails of different Landau bands are almost equivalent when the validity of the SdH formula indicates the insufficient localization in our system.

Acknowledgment

This work was funded by the NSC, Taiwan, and in part, by National Taiwan University (grant no: 101R7552-2 and 101R890932).

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