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Influence of Microwave Excitation-Power on the Narrow Negative Magnetoresistance Effect Around $B = 0$ T in the Ultra-High Mobility GaAs/AlGaAs 2DES

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In addition to the photo-excited zero-resistance states and radiation-induced magnetoresistance oscillations, which can be observed in the high-quality GaAs/AlGaAs two-dimensional electron system (2DES), magnetotransport studies of this 2DES also exhibit interesting dark magnetoresistance effects. Here, a narrow negative magnetoresistance (MR) effect that appears around zero field, and spans over about $-0.02\,\text{T} \leq B \leq 0.02\,\text{T}$ is examined. This experimental work aims to study the influence of microwave (MW) photo-excitation on this narrow negative-MR effect in high-mobility GaAs/AlGaAs 2DES. Experimental data exhibit that the observed negative magnetoresistance effect disappears with increasing MW power. For example, the change in magnetoresistance (ΔR_{xx}) due to the narrow negative-MR effect drops by $\approx$50% upon increasing the source power up to about 8 mW. Further analysis shows that the zero-field resistance monotonically increases with increasing the power, suggesting that electron heating due to the energy absorbed from the radiation field accounts for the observed quenching of the narrow negative-MR effect.

1. Introduction

Low temperature transport studies of high mobility ($\mu \geq 10^7$ $\text{cm}^2\,\text{V}^{-1}\text{s}^{-1}$GaAs/AlGaAs two-dimensional electron systems (2DES) grown by molecular beam epitaxy (MBE) have shown that the transport/elastic scattering length of these device structures can be comparable with the dimensions of the specimens even in the mm scale.[1–4] Thus, quasi-ballistic transport is possible in such specimens in the absence of a magnetic field. This feature has opened up the possibility to explore and understand new physical phenomena in high quality GaAs/AlGaAs samples. The novel physical phenomena include both photo-excited magneto transport effects and dark transport effects. Recent experimental[5–28] and theoretical[29–47] studies of high mobility GaAs/AlGaAs 2DES under low energy photo excitation, has demonstrated interesting novel photo-excited magneto-transport effects such as zero resistance states and associated radiation induced magnetoresistance oscillations. On the other hand, dark magnetoresistance properties, such as negative-MR effects exhibited by high-mobility samples, have also attracted experimental and theoretical interest among the researchers aiming to further understand the transport mechanism in these specimens.[49–55,3,56–61]

As far as the dark magnetoresistance properties of high mobility GaAs/AlGaAs 2DES are concerned, our previous reports[3,59,67] exhibit two distinct dark MR effects, which are: 1) negative Giant Magnetoresistance (negative-GMR) effect and 2) narrow negative MR effect around $B = 0$ T. Experimental studies have shown that the negative-MR effect around zero magnetic fields is temperature dependent (i.e., $T \geq 1$ K).[4,48] However, another study reported a temperature (i.e., $T \leq 800$ mK) invariance of the narrow negative magnetoresistance effect.[55] In the 1980s, studies on the lower mobility ($\approx 10^5\,\text{cm}^2\,\text{V}^{-1}\text{s}^{-1}$) 2DES,[62–64] the temperature dependent conductivity drop at the zero magnetic field was viewed as either localization or carrier interaction effect. Even though this narrow negative-MR feature in GaAs/AlGaAs 2DES appears like well known weak-localization effect,[65,62] due to low disorder and long elastic mean free paths, these modern high-mobility specimens do not satisfy requirements for the diffusive transport – a necessary condition for the observability of weak localization. Temperature dependent negative-MR effect in modern 2DES systems has also been theoretically modeled by considering that the electron transport occurs due to the formation of a viscous flow of an electron fluid.[66]

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Yet, it appears that more experimental and theoretical investigations are required to further understand the exact origin of this narrow negative MR effect in high-mobility GaAs/AlGaAs 2DES. Our experimental studies on high-mobility GaAs/AlGaAs 2DES exhibit that the microwave (MW) photo-excitation modifies the narrow negative MR effect around zero magnetic field. The motivation of this study is to understand the influence of incident MW power on the narrow negative-MR effect in high-mobility GaAS/AlGaAs 2DES. Thus, we examine the experimentally observed small and narrow negative magnetoresistance effect as a function of incident MW power.

2. Experimental Section

Four terminal electrical measurements were carried out on high mobility GaAs/AlGaAs 2DES Hall bar device structures grown using the MBE method. We utilized the typical low-frequency lock-in based techniques to perform the diagonal magnetoresistance, R_{xx} measurements. The heterostructure consists of (from bottom to top) 5000 Å GaAs-substrate/100 × (100 Å AlGaAs|30 Å GaAs)-superlattice/12 000 Å GaAs/700 Å AlGaAs/5 Å Si δ-doping/2400 Å AlGaAs/100 Å GaAs layers. The doping of the Si δ-layer is about $\approx 10^{12}\,\text{cm}^{-2}$. Since the 200 µm wide Hall bars included voltage probes spaced by 200 µm, the effective length-to-width (L/W) ratio for the measurements presented here is $L/W = 1$, thus one might set the diagonal resistance $R_{xx} = \rho_{xx}$, where ρ_{xx} is the diagonal resistivity. 2D electron mobility μ and the density n of the sample at 1.60 K were $\mu = 1.18 \times 10^7\,\text{cm}^2\,\text{V}^{-1}\text{s}^{-1}$ and $n = 2.4 \times 10^{11}\,\text{cm}^{-2}$, respectively. The sample was mounted at the end of a cylindrical waveguide which was used to photo-excite the sample with MW of frequency $f = 48.5$ GHz. The sample was placed inside a variable temperature insert, within a superconducting solenoid in the $B \perp I$ configuration. In this experiment, the incident MW power P was parametrically varied by means of an attenuator system. The lock-in voltages V_{xx} were recorded by collecting magnetic field (B) sweeps at a fixed MW power at 1.60 K. The diagonal magnetoresistance was calculated using the relationship $R_{xx} = V_{xx}/I_{ac}$.

3. Results and Discussion

Figure 1 exhibits the magnetoresistance data under dark (dashed lines) and illumination (solid lines) of MW with frequency $f = 48.5$ GHz, and power P as the parameter. The vertical arrow indicates the increasing MW source-power from 0 to 11.5 mW. This figure shows typical magnetoresistance effects of a high-mobility GaAs/AlGaAs 2DES over the magnetic field range of $-0.045\,\text{T} \leq B \leq 0.045\,\text{T}$, measured at low temperature ($T = 1.60$ K). At $|B| \geq 0.02$ T, one can observe well-known MW induced magnetoresistance oscillations, which initially increases its oscillation amplitude and then decreases again with further increasing the power. In addition to the oscillatory MR effect, the shaded region of the Figure 1 exhibits a non-oscillatory magnetoresistance feature, which is the main focus of this study. The non-oscillatory narrow negative magnetoresistance effect spans over the B-field range of $-0.02\,\text{T} < B < 0.02\,\text{T}$, in both conditions, i.e., with (solid lines) and without (dashed-line)

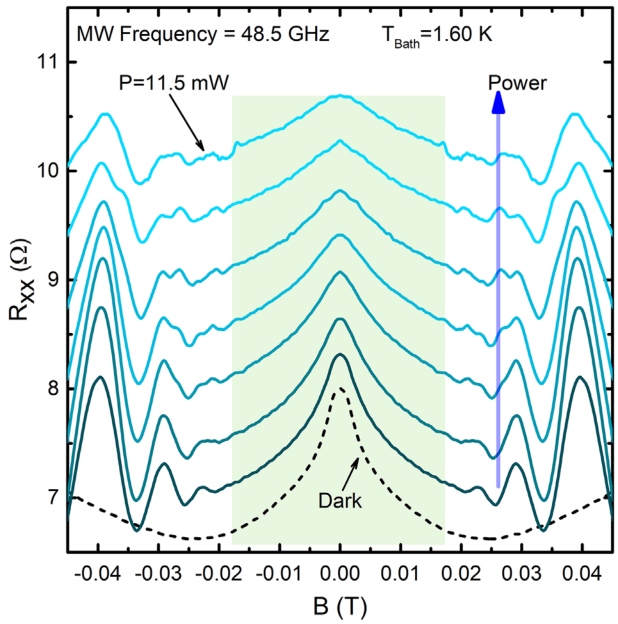

Figure 1. Magnetoresistance data of GaAs/AlGaAs two-dimensional electron system at bath temperature $T_{Bath} = 1.60$ K. Solid lines exhibit the experimental magnetoresistance data, i.e., R_{xx} versus B, over the magnetic field range of $-0.045\,\text{T} \leq B \leq 0.045\,\text{T}$. Radiation-induced magnetoresistance oscillations span over the range of $|B| \geq 0.02$ T, under the excitation of microwaves with frequency $f = 48.5$ GHz. Non-oscillatory portion of the magnetoresistance data appears around the zero magnetic field over a narrow range (i.e., $-0.02\,\text{T} < B < 0.02\,\text{T}$). The vertical arrow indicates the direction of increasing microwave power, from 0 to 12 mW. Dashed line exhibits the dark curve obtained in the absence of microwave excitation.

MWs. Surprisingly, the full width at half Maximum (FWHM) of the non-oscillatory narrow negative-MR peak appears to increase as a function of MW power, indicating that the MW power strongly modifies the negative-MR effect around the zero field in these GaAs/AlGaAs 2DES. Also, the diagonal resistance R_{xx} around $B = 0$ T increases with increasing MW power.

Figure 2 exhibits a further analysis of the non-oscillatory part or the narrow negative-MR effect of the magnetoresistance curves. Here, in Figure 2, the left ordinate exhibits the calculated change in magnetoresistance, that is, ΔR_{xx}, due to the narrow negative-MR feature. In this study, ΔR_{xx} was calculated using the expression, $\Delta R_{xx} = |R_{xx}(B) - R_{xx}(0)|$, where, $R_{xx}(B)$ is the magnetoresistance at a given B field and $R_{xx}(0)$ is the zero field resistance. Figure 2 (left-ordinate) shows such calculations of ΔR_{xx} using data at two different magnetic fields, those are $B = 0.01$ T and $B = 0.02$ T, as labeled in the panel. One can clearly observe that the magnetoresistance correction due to negative-MR effect around zeros field decreases with increasing the radiation power. For example, ΔR_{xx} at $B = 0.02$ T drops by $\approx 50\%$ upon increasing the radiation power up to ≈ 8 mW.

In our recent report, we discussed the effect of bath temperature on the narrow negative-MR in high-mobility GaAs/AlGaAs 2DES device structures. Experimental results of the study showed that the conductivity correction due to the

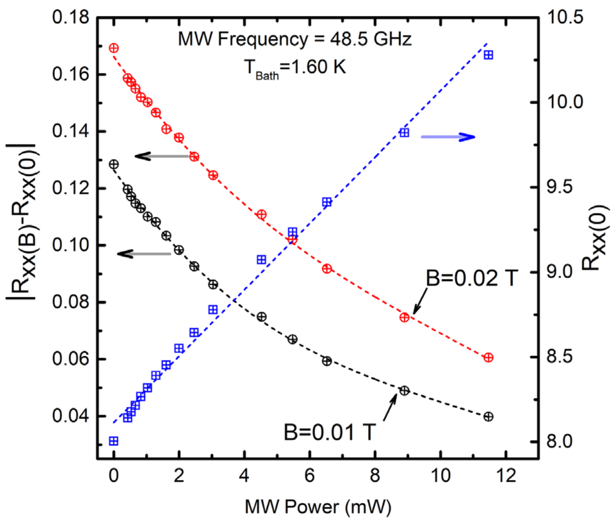

Figure 2. This figure exhibits the influence of MW power on the: 1) (left-ordinate) Change in magnetoresistance ΔR_{xx}, calculated using zero-field resistance, $R_{xx}(0)$ and magnetoresistance values, $R_{xx}(B)$ where $B = 0.01$ T and $B = 0.02$ T, as shown by arrows in the graph. The ΔR_{xx} is given by $\Delta R_{xx} = |R_{xx}(B) - R_{xx}(0)|$. 2) (right-ordinate) Zero field resistance, $R_{xx}(0)$. The dashed-lines are guides to the eye.

negative-MR effect decreases with increasing the bath temperature.[4] A closer examination of the temperature dependent data in ref. [4] and the radiation power dependent data in the Figure 1 suggests that the influence of these two parameters on the narrow negative-MR effect around zero field is similar. In other words, by increasing either bath-temperature or the radiation power one might expect a reduction in the magnetoresistance correction around zero field due to the narrow negative-MR effect. On the other hand, some experimental reports and theoretical predictions suggest a possible electron heating effect in 2DES under illumination with MWs.[36,19,68] The theory by Lei et al.[36] suggests that the maximum MW energy absorption rate in GaAs-based 2DES occurs when the $\omega_c/\omega = 1$, and quite a bit less at its harmonics, where ω_c is the cyclotron frequency given by $\omega_c = eB/m^*$ and $\omega = 2\pi f$. Here e, m^*, and f are the elementary charge, effective mass of the carriers, and frequency of the incident radiation, respectively. At low magnetic fields, which is smaller than the cyclotron resonance field, such as in the vicinity of zero field, GaAs/AlGaAs 2DES absorbs MW radiation energy through inter-Landau level transitions. Even though the energy absorption rate is small in high-mobility 2DES at low temperatures $\approx$1 K, electron heating can be significant, because, in the same time, the energy dissipation rate to the lattice through electron-phonon scattering is also small.[36] These mechanisms may lead to increase the effective electron temperature of the 2DES. In this process, the absorption of MWs may strengthen the thermalizing trend of the system by enhancing the electron temperature. The right ordinate in Figure 2 exhibits zero field resistance ($R_{xx}(0)$) as a function of incident MW power. Here, the $R_{xx}(0)$ increases monotonically with increasing power. As previously reported in the ref. [68] and as shown in the Figure 2 (right-ordinate), the increase in zero field resistance under photo-excitation suggests that the absorption of energy from the MW radiation field increases the electron temperature of the 2DES well above the lattice temperature. Therefore, one can observe a similar behavior in the narrow negative-MR, as it is observed in the temperature study, by illuminating the specimens with relatively high power radiation.

4. Conclusion

This study reports the influence of MW power on the narrow negative magnetoresistance effect that appears around zero magnetic field in the high-mobility GaAs/AlGaAs 2DES. The aim has been to understand the behavior of the narrow negative MR effect at elevated MW powers. Experimental results show that the narrow negative MR effect is strongly modified by the applied MW of $f = 48.5$ GHz. The magnetoresistance correction due to negative-MR effect decreases with increasing MW power and the observations can be understood as an electron heating effect induced by the absorbed energy from the MW radiation. However, further experiments and analysis appear necessary to fully understand the influence of MW on the narrow negative MR effect.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

electron scattering, magneto-resistance, microwaves, two-dimensional electron systems

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