MRS Advances © 2020 Materials Research Society
DOI: 10.1557/adv.2020.30

Influence of microwave photo-excitation on the transport properties of the high mobility GaAs/AlGaAs 2D electron system

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ABSTRACT

We examined the influence of the microwave power on the diagonal resistance in the GaAs/AlGaAs two dimensional electron system (2DES), in order to extract the electron temperature and determine microwave induced heating as a function of the microwave power. The study shows that microwaves produce a small discernable increase in the electron temperature both at null magnetic field and at finite magnetic fields in the GaAs/AlGaAs 2DES. The heating effect at null field appears greater in comparison to the examined finite field interval, although the increase in the electron temperature in the zero-field limit appears smaller than theoretical predictions.

INTRODUCTION

Photoexciting a 2D electron system at liquid helium temperatures in the presence of a weak perpendicular magnetic field can produce a vanishing resistance state [1-3]. Such radiation-induced zero-resistance states and associated magnetoresistance oscillations have been a topic of interest in the study of transport in low dimensional systems [1-28]. Radiation- induced magnetoresistance oscillations in a high quality 2DES show periodicity with the inverse magnetic field, with 1/4 circle shifted extrema with respect to cyclotron resonance and their harmonics [1]. At the lowest temperatures and modest microwave intensity, the oscillatory minima evolve into zero resistance states. The 1/4 circle phase shift, the non-linear behavior of the microwave induced oscillation amplitude with microwave power [8,14], correlation between the magnetoresistance oscillation and microwave reflection from 2DES [15], polarization dependency [7-8,16-17], and magnetoresistance oscillation under bichromatic photo-excitation [18-20] are other interesting experimental observations in this field. Some of these experimental observations have been examined by displacement model [21], the microwave driven electron orbital model [22], the inelastic model [23], memory effect theory [24], and synchronization theory [25]. A balance equation model applied to nonlinear magneto transport, which covers both separated and overlapping Landau-level regimes, and takes full account of multi photon assisted electron transition between various states, as well as role of electron temperature is of special interest for this study which examines electron heating under photoexcitation [26,27]. Here, the electron temperature has been examined by balancing the energy absorption from the radiation field and the energy dissipation to the lattice through electron phonon couplings.

Thus, we examine electron heating induced by monochromatic microwaves in 2DES in GaAs/AlGaAs heterostructure, in the low field Shubnikov-de Haas (SdH) oscillation region as well as at zero magnetic field. Our study indicates that microwave induced electron heating in the high quality 2DES in GaAs/AlGaAs heterostructure produces a small discernible temperature increase in both examined regions, in qualitative agreement with theoretical predictions. The electron temperature at null magnetic field appears greater in comparison to the examined finite magnetic field interval. At finite magnetic fields, no discernible difference is observed for the different frequencies examined here.

EXPERIMENT

Lock-in-based four terminal electrical measurements were performed on photolithographically prepared Hall bar devices based on molecular beam epitaxy grown GaAs/AlGaAs heterojunctions. At 1.7 K, the electron density was 2.4×10^{11}cm^{-2} and the mobility was 8.4×10^{6} cm^{2}/Vs. Hall bar device was illuminated with linearly polarized microwaves for photo-excited transport measurements. The polarization of incident microwave was parallel to the long axis of the Hall bar device. The microwave frequency spanned $30< f <50$ GHz. The diagonal voltage in the device was examined at T = 1.7 K at several microwave-source power levels.

RESULTS AND DISCUSSION

Photo-excited transport data at T=1.7K are shown in Figure 1(a). Note two observable characteristics in the R_{xx} vs. B traces with the parametric variation of the incident microwave power: (1) the R_{xx} at zero magnetic field is up-shifted to higher resistance with the increment of the microwave power as shown in Figure 1(a), and (2) microwave radiation-induced oscillations are observable to B <0.2 T. We attribute feature (1) to a heating effect resulting from microwave photoexcitation because the effect of increasing the microwave power on R_{xx} is analogous to the effect of increasing the bath temperature, in the absence of the microwave photo-excitation. Our goal here is to convince of electron heating and to extract the increment in the electron temperature resulting from microwave photo-excitation.

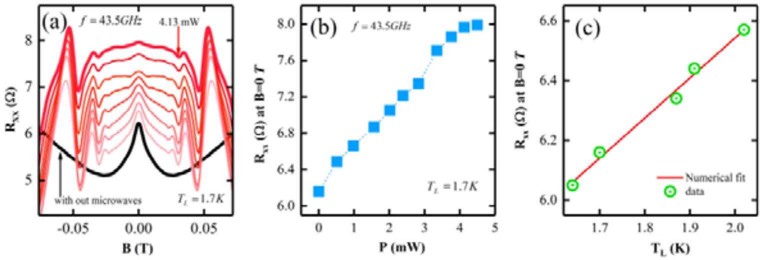

Figure 1. (a) The diagonal resistance R_{xx} is shown vs. the magnetic field B over the range $-0.076 < B < 0.076$ T , at 1.7 K for 43.5 GHz microwave excitation. The R_{xx} is up-shifted with the increment of the incident microwaves. (b) The R_{xx} at zero magnetic field extracted from the Figure 1(a) is plotted as a function of microwave powers. (c) The R_{xx} at zero magnetic field as a function of sample bath or lattice temperature (T_L).

Consider the up-shifting of the zero field R_{xx}, observable in the Figure 1(a), which has been re-plotted as a function of the source microwave power in Figure 1(b). Figure 1(b) shows that R_{xx} increases monotonically with the microwave power, P. Compare these results with a plot of the dark R_{xx} at B=0 T as a function of the bath or lattice temperature, T_L which is shown in Figure 1(c). Figure 1(c) indicates that R_{xx} increases with T_L in a similar manner in which it increases with P in Figure 1(b). It is worth to mention that heating with lattice temperature and microwaves are similar but maybe not exactly equivalent. Here, the red solid line is a least squares linear fit, which gives the diagonal resistance as a function of the lattice temperature: $R_{xx} = R_{xx}(T_L)$, i.e.,

$$R_{xx}\,[\Omega] = 1.34\,[\Omega/\mathrm{K}]T_L[\mathrm{K}]+3.86[\Omega] \qquad (1)$$

This relation between the R_{xx} and T_L the can be inverted to obtain $T=T(R_{xx})$. Such inversion was carried out so that the zero-magnetic-field R_{xx} can serve as a temperature gauge, even in the presence of microwave excitation. In the microwave irradiated condition, however, the diagonal resistance serves as a gauge of the electron temperature, T_e, not the lattice temperature, T_L, since the electron system can potentially be decoupled from the lattice or bath in the presence of such drive. According to results exhibited here, the resistance in the absence of magnetic field is sensitive to microwave photoexcitation. This could mean that the mobility decreases with increasing microwave power.

Next, we consider microwave photoexcitation in the regime of SdH oscillations (Fig. 2). SdH oscillations appear at higher magnetic fields when the thermal broadening of the electron distribution is smaller than the energy of Landau quantization, and it is quickly suppressed by the rising temperature $k_BT > \hbar\omega_C$, where k_B is Boltzmann constant and $\hbar$ is reduced Planck constant.

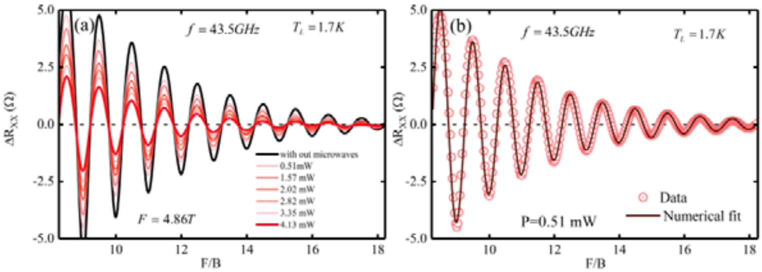

Figure 2. (a) Shubnikov-de Haas (SdH) oscillations in ΔR_{xx} are plotted versus the F/B at different microwave power at a bath temperature 1.7 K. Here, B is the magnetic field and F is the frequency of the SdH oscillations. (b) The SdH oscillations have been fit over the range of $8 < F/B < 18$. The open red circles represent the ΔR_{xx} data while the solid black line represents the numerical fit. Such fits serve to extract the electron temperature, T_e, as a function of the microwave power.

We examined the SdH line-shape over the span $8 < F/B < 18$, where F is the SdH frequency. In order to facilitate line-shape fits, a monotonic background R_{xx} term was subtracted from the raw magneto-resistance data to obtain the oscillatory ΔR_{xx} term. Then ΔR_{xx} vs. the inverse magnetic field was plotted for different microwave powers as shown in Figure 2 (a). To extract the electron temperature from the SdH oscillations, a standard nonlinear least square fit (NLSF) was performed on ΔR_{xx} data with an exponentially damped sinusoidal function [8,29], i.e.,

$$\Delta R_{xx} = -A \exp\left(-\lambda (T_L + T_e).(m^*/m_e)/B\right) \cos\left(2\pi F/B\right) \quad (2)$$

Where A is the oscillation amplitude, $\lambda = 2\pi^2 k_B m_e/e$, m^*/m_e is effective mass ratio of electrons, T_L is the lattice temperature, T_e is the electron temperature increment with respect to the lattice. In practice, it turned out that Dingle temperature is very small compared to T_L. As an example, the fit of the ΔR_{xx} data at 1.7 K for $P = 0.51$ mW is shown in Figure 2(b) as solid black line. From such fits, we extracted the electron temperature, T_e, in the regime of the SdH oscillations.

We compare the heating, $\Delta T_e = T_L - T_e$, at zero magnetic field extracted from the zero-field ΔR_{xx} and, at finite magnetic fields extracted from the SdH oscillations for 43.5 and 48.5 GHz in Figure 3. The electron temperatures increased with the incident microwave power, both in the absence of a magnetic field and also at small finite magnetic fields. However, the increase in the electron temperature at zero magnetic field under microwave excitation is greater than the extracted electron temperature increase over the SdH oscillation region. These results are in qualitative agreement with the theoretical predictions, [27], which suggest that the increase in the electron temperature should be smaller in the regime of the SdH oscillations than in the absence of a magnetic field. However, theory predicts that the increase of the electron temperature at zero magnetic field can be as large as 10-20 K at $T_L \approx 1$ K, which is not confirmed in our study. We attribute differences between experiment and theory to differences in parameters in experiment and theory, and also to the point that microwave power here is the power at the source while theory considers power at the sample. For example, theory also assumes a higher mobility. At a higher mobility, the 2DES provides a longer elastic mean free path and phase coherence length. It appears reasonable that over these longer length scales/times, more energy can be absorbed from the radiation field, leading to enhanced heating. That is, a lower mobility in our device in comparison to the theoretical studies might lead to a reduced heating effect in experiment.

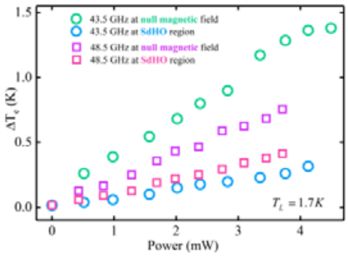

Figure 3. The increase in the electron temperature above the bath temperature (ΔT_e) due to microwave photoexcitation, as function of the microwave power, both at null magnetic field and in the regime of SdH oscillations, for two microwave frequencies, 43.5 and 48.5 GHz.

CONCLUSION

In conclusion, we have suggested that the microwave photo-excitation generates a small perceptible carrier heating both at zero magnetic field and at finite magnetic fields in the GaAs/AlGaAs 2DES. The heating effect at finite magnetic field appears smaller in comparison to the zero magnetic field case, in agreement with theoretical calculations. [26, 27] In addition, our results suggest more heating at null magnetic field at lower microwave frequencies, although in the SdH magnetic field region, there is no significant difference.

ACKNOWLEDGEMENTS

This work was supported by the NSF under ECCS-1710302, and the Army Research Office under W911NF-15-1-0433.

References

[1] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Nature (London) 420, 646 (2002), Phys. Rev. B 69, 193304 (2004); Phys. Rev. Lett. 92, 146801 (2004).
[2] M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K.W.West, Phys. Rev. Lett. 90, 046807 (2003).
[3] R. G. Mani, V. Narayanamurti, K. von Klitzing, J. H. Smet, W. B. Johnson, and V. Umansky, Phys. Rev. B 70, 155310 (2004); Phys. Rev. B. 69, 161306 (2004).
[4] A. E. Kovalev, S. A. Zvyagin, C. R. Bowers, J. L. Reno, and J. A. Simmons, Solid State Commun. 130, 379 (2004).
[5] B. Simovic, C. Ellenberger, K. Ensslin, H. P. Tranitz, andW. Wegscheider, Phys. Rev. B 71, 233303 (2005).
[6] R. G. Mani, Physica E 22, 1 (2004); Physica E 25, 189 (2004); Physica E 40, 1178 (2008); Phys. Rev. B 72, 075327 (2005); Appl. Phys. Lett. 92 102107 (2008); Int. J. Mod. Phys. B 18, 3473 (2007); Appl. Phys. Lett. 91, 132103 (2007); Sol. St. Comm. 144, 409 (2007).
[7] A. N. Ramanayaka, et al., Phys. Rev. B 83, 165303 (2011); Phys. Rev. B 85, 205315 (2012).
[8] R. G. Mani et al., Sci. Rep. 3, 3478 (2013) DOI:10.1038/srep03478; Sci. Rep. 3, 2747 (2013); DOI:10.1038/srep02747; Phys. Rev. B 81, 125320 (2010); Phys. Rev. B 37, 4299 (R), (1988); Z. Phys. B 92 335 (1993); Phys. Rev. B 84, 085308 (2011).
[9] Z. Wang, et al., Sci. Rep. 6, 38516; (2016).
[10] R.L. Samaraweera, et al., Sci. Rep.7, 5074 (2017).
[11] H.-C. Liu, et al., J. Appl. Phys. 117, 064306 (2015); Sci. Rep. 8, 7878 (2018) - DOI: 10.1038/s41598-018-26009-z
[12] C. R. Munasinghe, et al., J. Phys.: Condens. Matter 30 315701(2018).
[13] J. Iñarrea and G. Platero, Appl. Phys. Lett. 89, 172114 (2006).
[14] J. Iñarrea, R. G. Mani, and W. Wegscheider, Phys. Rev. B 82, 205321 (2010).
[15] T. Ye et al., Appl. Phys. Lett. 103, 192106 (2013); 102, 242113 (2013).
[16] T. Ye, et al., Phys. Rev. B 89, 155307 (2014); Appl. Phys. Lett. 105, 191609 (2014); Sci.Rep.5, 14880 (2015).
[17] J. Iñarrea, J. Appl. Phys. 113, 183717 (2013).
[18] M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K.W.West, Phys. Rev. Lett. 96, 236804 (2006).
[19] B. Gunawardana, et al., Phys. Rev. B 95, 195304 (2017).
[20] X. L. Lei and S. Y. Liu, Appl. Phys. Lett. 89, 182117 (2006).
[21] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. 91, 086803 (2003).
[22] J. Iñarrea and G. Platero, Phys. Rev. Lett. 94, 016806 (2005).
[23] I. A. Dmitrievet et al., Phys. Rev. B 71, 115316 (2005).
[24] Y. M. Beltukov and M. I. Dyakonov, Phys. Rev. Lett. 116, 176801 (2016).

[25] O. V. Zhirov, A. D. Chepelianskii, and D. L. Shepelyansky, Phys. Rev. B 88, 035410, (2013).
[26] X. L. Lei and S. Y. Liu, Phys. Rev. B 72, 075345 (2005); Phys. Rev. B 86, 205303 (2012).
[27] X. L. Lei, Materials Science and Engineering: R: Reports (Amsterdam) 70, 126-150 (2010). DOI- doi.org/10.1016/j.mser.2010.06.006.
[28] A. D. Chepelianskii, et al., Eur. Phys. J. B 60, 225-229 (2007); Phys. Rev. B 80, 241308(R) (2009)
[29] L. M. Lifshitz and A. M. Kosevich, J. Phys. Chem. Solids 4, 1 (1958) [Sov. Phys. JETP 4, 173 (1958)].