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A. N. Ramanayaka, R. G. Mani, and W. Wegscheider

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# Microwave-induced electron heating in the regime of radiation-induced magnetoresistance oscillations

A. N. Ramanayaka and R. G. Mani

*Georgia State University, Atlanta, GA 30303.*

W. Wegscheider

*Laboratorium für Festkörperphysik, ETH Zürich, 8093 Zürich, Switzerland*

## Abstract

We examine the influence of microwave photoexcitation on the amplitude of Shubnikov-de Haas (SdH) oscillations in a two dimensional GaAs/AlGaAs electron system in a regime where the cyclotron frequency,  $\omega_c$ , and the microwave angular frequency,  $\omega$ , satisfy  $2\omega \leq \omega_c \leq 3.5\omega$ . A SdH lineshape analysis indicates that increasing the incident microwave power has a weak effect on the amplitude of the SdH oscillations, in comparison to the influence of modest temperature changes on the dark-specimen SdH effect. The results indicate negligible electron heating under modest microwave photoexcitation, in good agreement with theoretical predictions.

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## INTRODUCTION

The GaAs/AlGaAs quasi two-dimensional electron system has served as the basis for many interesting developments in modern condensed matter physics.[1, 2] In the recent past, photo-excited transport studies in this system have become a topic of experimental[3–25] and theoretical[26–47] interest since the observation of zero-resistance states and associated magneto-resistance oscillations in the microwave excited two-dimensional electron system.[3, 4]. Periodic in  $B^{-1}$  radiation-induced magnetoresistance oscillations, which lead into the radiation-induced zero-resistance states, are now understood to be a consequence of radiation-frequency ( $f$ ), and magnetic field ( $B$ ) dependent, scattering at impurities [26, 28, 29] and/or a change in the distribution function,[5, 35] while vanishing resistance is thought to be an outcome of negative resistance instability and current domain formation.[27, 44] Although there has been much progress in this field, there remain many aspects, such as indications of activated transport, the overlap with quantum Hall effect, and the influence of the scattering lifetimes, that could be better understood from both the experimental and theoretical perspectives.

A further topic of experimental interest is to examine the possibility of electron heating, as theory has,[31, 34, 36] in consistency with common experience, indicated the possibility of microwave-induced electron heating in the high mobility 2DES in the regime of the radiation-induced magnetoresistance oscillations. Not surprisingly, under steady state microwave excitation, the 2DES can be expected to absorb energy from the radiation field. At the same time, electron-phonon scattering can serve to dissipate this surplus energy onto the host lattice. Lei et. al [34] have determined the electron temperature,  $T_e$ , by balancing the energy dissipation to the lattice and the energy absorption from the radiation field, while including both intra-Landau level and inter-Landau level processes. In particular, they showed that the electron temperature,  $T_e$ , the longitudinal magnetoresistance,  $R_{xx}$ , and the energy absorption rate,  $S_p$ , can exhibit remarkable correlated non-monotonic variation vs.  $\omega_c/\omega$ , where  $\omega_c$  is the cyclotron frequency, and  $\omega = 2\pi f$ , with  $f$  the radiation frequency.[34] In such a situation, some questions of experimental interest then are: (a) How to probe and measure electron heating in the microwave-excited 2DES? (b) What is the magnitude of electron heating under typical experimental conditions? Finally, (c) is significant electron heating a general characteristic in microwave radiation-induced transport?

An approach to the characterization of electron-heating could involve a study of the amplitude of the Shubnikov-de Haas (SdH) oscillations, that also occur in  $R_{xx}$  in the photo-excited specimen. Typically, SdH oscillations are manifested at higher magnetic fields,  $B$ , than the radiation-induced magnetoresistance oscillations, i.e.,  $B > B_f = 2\pi f m^*/e$ , especially at low microwave frequencies, say  $f \leq 50GHz$  at  $T \geq 1.3K$ . On the other hand, at higher  $f$ , SdH oscillations can extend into the radiation-induced magneto-resistance oscillations. In a previous study, ref.[19] has reported that SdH oscillation amplitude scales linearly with the average background resistance in the vicinity of the radiation-induced resistance minima, indicating the SdH oscillations vanish in proportion to the background resistance at the centers of the radiation-induced zero-resistance states. Kovalev et. al [10] have reported the observation of a node in the SdH oscillations at relatively high- $f$ . Ref. [17] discuss SdH damping and a strong suppression of magnetoresistance in a regime where microwaves induce intra-Landau-level transitions. Both ref.[19] and ref. [10] examined the range of  $\omega_c/\omega \leq 1$ , whereas ref.[17] examined the  $\omega_c/\omega \geq 1$  regime.

From the theoretical perspective, Lei et al. have suggested that a modulation of SdH oscillation amplitude in  $R_{xx}$  results from microwave-electron heating. Further, they have shown that, in  $\omega_c/\omega \leq 1$  regime, both  $T_e$  and  $S_p$  exhibit similar oscillatory features, while in  $\omega_c/\omega \geq 1$  regime, both  $T_e$  and  $S_p$  exhibit a relatively flat response.

Here, we investigate the effect of microwaves on the SdH oscillations over  $2B_f \leq B \leq 3.5B_f$ , i.e.,  $2\omega \leq \omega_c \leq 3.5\omega$ , where  $B_f = 2\pi f m^*/e$ ,  $m^*$  is the effective electron mass, and  $e$  is the electron charge[3]. In particular, we compare the relative change in the SdH oscillation amplitude due to lattice temperature changes in the dark, with changes in the SdH amplitude under microwave excitation at different microwave power levels, at a constant bath temperature. From such a study, we extract the change in the electron temperature,  $\Delta T_e$ , induced by microwaves. In good agreement with theory, the results indicate  $\Delta T_e \leq 50mK$  over the examined regime.

## EXPERIMENT AND RESULTS

The lock-in based electrical measurements were performed on Hall bar devices fabricated from high quality GaAs/AlGaAs heterostructures. Experiments were carried out with the specimen mounted inside a waveguide and immersed in pumped liquid helium. The fre-

quency spanned  $25 \leq f \leq 50GHz$  at source power levels  $P \leq 5mW$ . Magnetic-field-sweeps of  $R_{xx}$  vs.  $P$  were carried out at  $1.6K$  at  $41.5GHz$ , and at  $1.5K$  at  $44GHz$  and  $50GHz$ .

Microwave-induced magneto-resistance oscillations can be seen in Fig. 1 at  $B \leq 0.175T$ , as strong SdH oscillations are also observable under both the dark and irradiated conditions for  $B \geq 0.2T$ . Over the interval  $2B_f \leq B \leq 3.5B_f$ , where the SdH oscillations are observable, one observes small variations in the background  $R_{xx}$  at higher power levels. Thus, a smooth  $R_{xx}$  background was subtracted from the magneto-resistance data. Figure 2 (a) - (f) shows the background subtracted  $R_{xx}$ , i.e.,  $\Delta R_{xx}$ , measured without (Fig. 2(a)) and with (Fig. 2(b)-2(f)) microwave radiation versus the inverse magnetic field,  $B^{-1}$ . To extract the amplitude of the SdH oscillations, we performed a standard Nonlinear Least Square Fit (NLSF) on  $\Delta R_{xx}$  data with a exponentially damped sinusoid, i.e.,  $\Delta R_{xx} = -Ae^{-\alpha/B} \cos(2\pi F/B)$ . Here,  $A$  is the amplitude,  $F$  is the SdH frequency, and  $\alpha$  is the damping factor. The fit results for the dark-specimen  $\Delta R_{xx}$  data are shown in the Fig. 2 (a) as a solid line. This panel suggests good agreement between data and fit in the dark condition. Similarly, we performed NLSFs of the  $\Delta R_{xx}$  SdH data taken with the microwave power spanning approximately  $0 \leq P \leq 3mW$ , see Fig. 2(b)- 2(f). Since the parameters  $\alpha$  and  $F$  are insensitive to the incident radiation at a constant temperature, we fixed  $\alpha$  and  $F$  to the dark-specimen constant values. In Fig. 2, panels (b) – (f) show the  $T = 1.5K$   $\Delta R_{xx}$  data (open circles) and fit (solid line) obtained with  $f = 44GHz$  for different power levels. The SdH amplitude  $A$  extracted from the NLSFs are exhibited vs. the microwave power in Fig. 2(g). Here,  $A$  decreases with increasing microwave power. Our analysis of other power-dependent data (not shown) yielded similar results.

Next, we examine the influence of temperature on the SdH oscillation amplitude. Thus, Fig.3(a) shows  $R_{xx}$  vs.  $B$  with the temperature as a parameter. It is clear, see the black solid lines, that increasing the temperature rapidly damps the SdH oscillations at these low magnetic fields. In order to extract the SdH amplitude from these data, we used the same fitting model,  $\Delta R_{xx} = -Ae^{-\alpha/B} \cos(2\pi F/B)$ , as described previously. But, for the  $T$ -dependence analysis,  $\alpha$  was separated into two parts,  $\alpha_{T_0}$  and  $\beta\Delta T$ , i.e.,  $\alpha = \alpha_{T_0} + \beta\Delta T$ , since we wished to relate the change in the SdH amplitude for a temperature increment to the observed change in the SdH amplitude for an increment in the microwave power at a fixed  $f$ . Here  $\alpha_{T_0}$  represents the damping at the base temperature, and  $\beta\Delta T$  is the additional damping due to the temperature increment,  $\Delta T = T - T_0$ . Now the fit function becomes

$\Delta R_{xx} = -Ae^{-(\alpha_{T_0} + \beta\Delta T)/B} \cos(2\pi F/B) = -A'e^{-\alpha_{T_0}/B} \cos(2\pi F/B)$ . Here,  $A' = Ae^{-\beta\Delta T/B}$  represents the change in the SdH oscillation amplitude due to the  $\Delta T$ . Note that the parameters  $\alpha_{T_0}$  and  $F$  can be extracted from the  $R_{xx}$  fit at the lowest  $T$  and set to constant values. Data fits to  $\Delta R_{xx} = -A'e^{-\alpha_{T_0}/B} \cos(2\pi F/B)$  are included in Fig. 3(a) as colored solid lines. Thus, the NLSF served to determine  $A'$  at each temperature. Fig. 3(b) shows the temperature dependence of  $A'$ , while the inset of Fig. 3(b) shows a semi-log plot of  $A'$  vs.  $T$ . The inset confirms an exponential dependence for  $A'$  on  $T$ , i.e,  $A' = Ae^{-\beta\Delta T/B}$ .

Experiments indicate that increasing the source-power monotonically decreases the SdH oscillation amplitude at the examined frequencies including  $44GHz$  (see Fig.2(g)),  $50GHz$  and  $41.5GHz$  (see Fig.4(a)). Since increasing the temperature also decreases the SdH oscillation amplitude (see Fig.3(b)), one might extract the electron temperature change under microwave excitation by inverting the observed relationship between  $A'$  and  $T$ , i.e., since  $A' = Ae^{-\beta\Delta T/B}$ ,  $\Delta T = -(B/\beta^{-1})(\ln A' + c)$ , where  $\beta$  is a constant. Thus, the dark measurement of the SdH amplitude vs. the temperature serves to calibrate the temperature scale vs. the SdH amplitude, and the slope of the solid line in Fig. 4(b) reflects the inverse slope of Fig. 3(b). Also plotted as solid symbols in Fig.4(b) are the  $A$  under microwave excitation at various frequencies and power levels. Here, one observes that the change in SdH amplitude induced by microwave excitation over the available power range is significantly smaller than the change in SdH amplitude induced by a temperature change of 0.9K. By transforming the observed change in  $A$  between minimum- and maximum- power at each  $f$  to a  $\Delta T_e$ , we can extract the maximum  $\Delta T_e$  induced by photo-excitation at each  $f$ , and this is plotted in Fig.4(c). Although the power at the sample can vary with  $f$ , even at the same source power, Fig.4(c) indicates that the maximum  $\Delta T_e$  scales approximately linearly with the peak source microwave power (see Fig.4(c) solid guide line). From Fig.4(c), it appears that  $\Delta T_e/\Delta P = 9mK/mW$ .

## DISCUSSION

According to theory,[31, 34, 36] steady state microwave excitation can heat a high mobility two-dimensional electron system. The energy gain from the radiation field is balanced by energy loss to the lattice by electron-phonon scattering. In ref. [34], Lei et al. suggest that longitudinal acoustic (LA) phonons provide for more energy dissipation than the transverse

acoustic (TA) phonons in the vicinity of  $T = 1K$  in the GaAs/AlGaAs system, if one neglects the surface or interface phonons. At such low temperatures and modest microwave power, away from the cyclotron resonance condition, where the resonantly absorbed power from the microwave radiation is not too large, and the electron temperature remains well below about  $20K$ , the longitudinal optical(LO) phonons do not influence the resistivity since the energy scale associated with LO-phonons is large compared to the energy scale for acoustic phonons. Within their theory, Lei et al.[34] show that the electron temperature follows the absorption rate, exhibiting rapid oscillatory behavior at low  $B$ , i.e.,  $\omega_c/\omega \leq 1$ , followed by slower variation at higher  $B$ , i.e.,  $\omega_c/\omega \geq 1$ . Indeed, even at the very high microwave intensities,  $P/A$ , e.g.  $4 \leq P/A \leq 18mW/cm^2$  at  $50GHz$ , theory does not show a significant change in the electron temperature for  $B \geq 2B_f$  except at  $P/A \geq 10.5mW/cm^2$ . Thus, theory indicates that the electron temperature is nearly the lattice temperature in low  $P/A$  limit especially for  $B \geq 2B_f$ , i.e.,  $\omega_c \geq 2\omega$ . In comparison, in these experiments, the source power satisfied  $P \leq 4mW$ , with  $A \approx 1cm^2$ , while the power at the sample could be as much as ten times lower due to attenuation by the hardware. Remarkably, we observe strong microwave induced resistance oscillations (see Fig.1) in the  $B \leq B_f$  regime at these low intensities. The results, see Fig. 4(c), indicate just a small rise,  $\Delta T \leq 50 \times 10^{-3}K$ , in the electron temperature,  $T_e$ , above the lattice temperature,  $T$ . Apparently, in the spirit of the Lei et al. theory,[34] the electron heating is negligible here because energy absorption rate is rather small over the investigated regime.

## SUMMARY AND CONCLUSIONS

In summary, this experimental study indicates that the perceptible effect of the incident microwave radiation on the amplitude of the SdH oscillations over the regime  $2\omega \leq \omega_c \leq 3.5\omega$ , when the microwave excitation is sufficient to induce strong microwave induced resistance oscillations, corresponds to a relatively small increase in the electron temperature, in good agreement with theoretical predictions.

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## FIGURE CAPTIONS

Figure 1) Microwave induced magneto-resistance oscillations and SdH oscillations in  $R_{xx}$  are shown at  $1.5K$  for  $44GHz$  at different power levels,  $P$ . A horizontal marker (green) shows the field range ( $2B_f \leq B \leq 7/2B_f$ ) where SdH fits were carried out.

Figure 2)(a) The background subtracted  $R_{xx}$ , i.e.,  $\Delta R_{xx}$ , in the absence of radiation (open circles) and a numerical fit (solid line) to  $\Delta R_{xx} = -Ae^{-\alpha/B} \cos(2\pi F/B)$  are shown here. Panels (b) – (f) show the  $\Delta R_{xx}$  and the fit at the indicated  $P$ . Panel (g) shows  $A$  vs.  $P$  at  $44GHz$ .

Figure 3) (a) Temperature ( $T$ ) dependence of  $R_{xx}$  is shown for  $1.26K \leq T \leq 2.12K$ . The black lines show the data, and the colored lines indicate the fits. (b) The exponential variation of the amplitude  $A'$  with  $T$  is shown here. The inset confirms that  $\log(A')$  is linear in  $T$ .

Figure 4)(a) Variation of  $A$  with  $P$  is shown for  $f = 41.5GHz$  (left axis) and  $f = 50GHz$  (right axis). (b) The effect of  $T$  and  $P$  on  $A'$  (solid line) and  $A$  (solid symbols) are shown here. Corresponding  $T$ -change was determined through the exponential relation between  $\Delta T$  and  $A'$ . Panel (c) shows a plot of maximum  $\Delta T_e$  vs peak- $P$  (solid symbols), with a line to guide the eye.

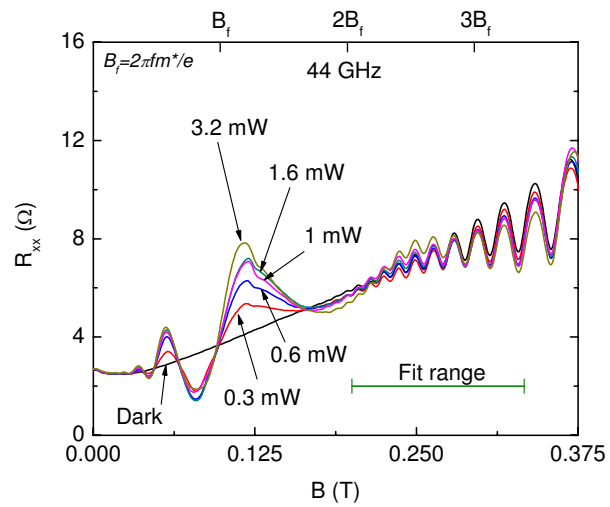


FIG. 1:

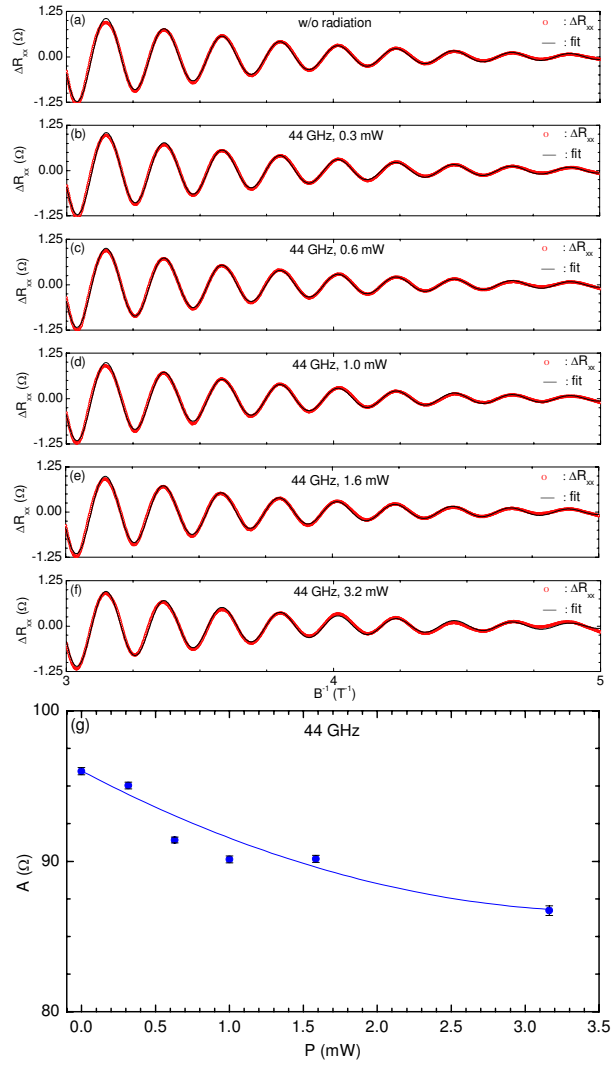


FIG. 2:

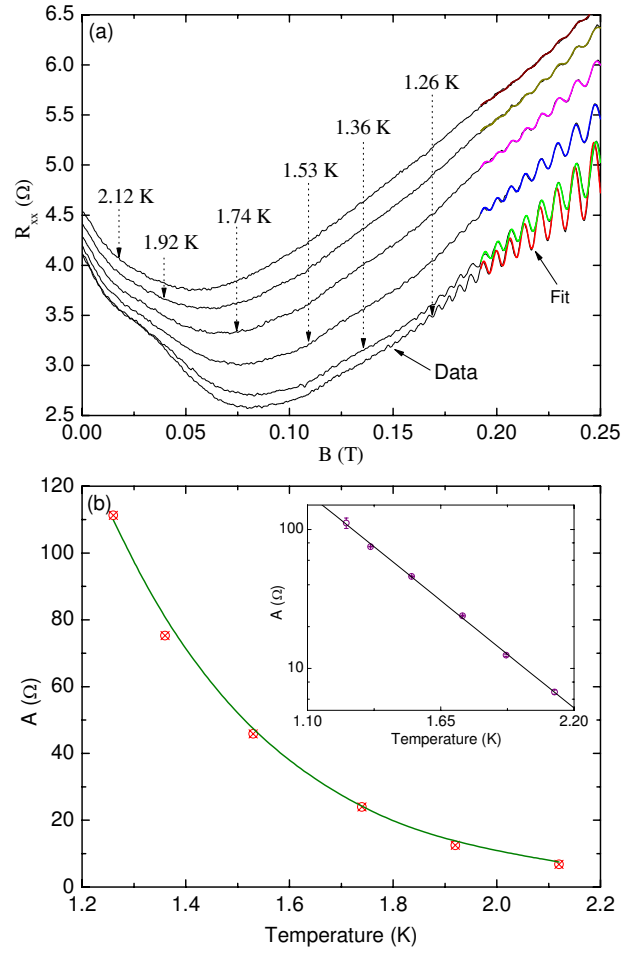


FIG. 3:

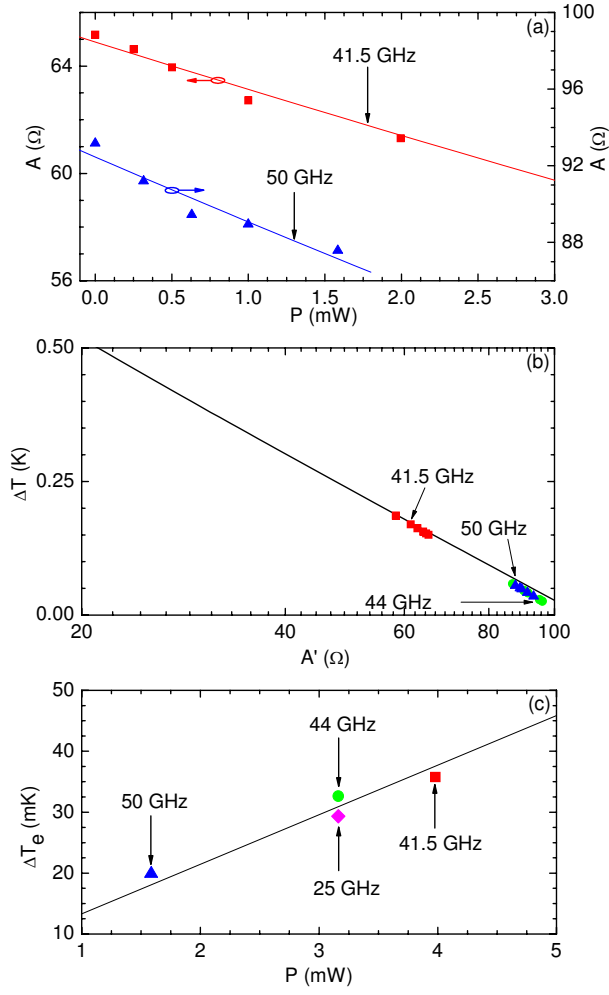


FIG. 4: