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Behaviour of Bichromatic Microwave Induced Magneto-resistance Oscillations in the High Mobility GaAs/AlGaAs 2D electron System

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Abstract: Microwave radiation-induced magneto-resistance oscillations are examined under bichromatic excitation for various frequency combinations in order to obtain a better understanding of the lineshape observed in the dual excitation experiment of the high mobility GaAs/AlGaAs 2D electron system. Here, we examine superposition- or lack thereof- in the lineshape observed in the bichromatic experiment, and report a trend observed between the monochromatic and bichromatic responses of the oscillatory diagonal resistance.

Introduction

Microwave radiation-induced magnetoresistance oscillations refer to the B^{-1}-periodic oscillatory variation in the diagonal (R_{xx}) - and off-diagonal (R_{xy}) resistance observed under microwave excitation in the 2D electron system under the influence of a transverse magnetic field, B.[1-24] Such oscillations exhibit a so-called ¼ -cycle phase shift, non-linear variation in the oscillatory amplitude with microwave power,[13,21,22] sensitivity in the oscillatory amplitude to the orientation of the linearly polarized microwaves with respect to the device,[15] etc. Many theoretical explanations have been proposed to help understand associated phenomena [25-42], including, for example, mechanisms based on (a) the scattering of electrons by phonons and impurities between Landau levels [26,30,33], (b) the periodic motion of electron orbit centers under microwave irradiation,[27,35] and (c) the re-collision of cyclotron electrons from scattering centers [42].

In order to obtain a better understanding of both the underlying physical mechanism and the experimental phenomenology, microwave radiation-induced magneto-resistance oscillations in the diagonal resistance R_{xx} are examined here under bichromatic excitation for various frequency combinations. Thus, the 2D electron system was photo-excited with microwave frequencies at both f_1 and f_2, which were chosen to realize different f_1/f_2 ratios ranging from $1.84 < f_1/f_2 < 3.4$. In addition, the microwave power was changed systematically to study the evolution of the lineshape in going from the monochromatic to the bichromatic photoexcitation situation.

1. Experiment and results

Measurements were carried out on a GaAs/AlGaAs 2D heterostructure sample with an electron density of 3.3×10^{11} cm^{-2} and mobility 14.6×10^{6} cm^2/Vs at 1.8K. Two microwave sources served to produce microwaves at two different frequencies and bichromatic photoexcitation of the specimen was realized by combining the output of these two sources with a waveguide coupler. In experiment, the sample was first illuminated with monochromatic microwaves at frequency f_1, with the other microwave source at f_2 switched off, to obtain the R_{xx} vs. B response at f_1. Then, the source at f_1 was switched off, and the source at f_2 was switched on, to obtain the R_{xx} vs. B response at f_2. Finally, the sources at both f_1 and f_2 were switched on for the bichromatic photo-excitation experiment. Traces of R_{xx} vs. B obtained for frequency combinations of f_1 = 90.6GHz and f_2 = 34.65GHz, f_1 = 90.6GHz and f_2 = 41.0GHz and f_1 = 90.6GHz and f_2 = 48.7GHz are shown in figure 1.

A study of the experimental results of Fig. 1 suggests that the bichromatic microwave response of R_{xx} seems to follow the low frequency monochromatic microwave response of R_{xx} at low magnetic fields. However, the bichromatic response tends to deviate towards the high frequency monochromatic microwave response when the magnetic field strength increases, for all the examined combinations.

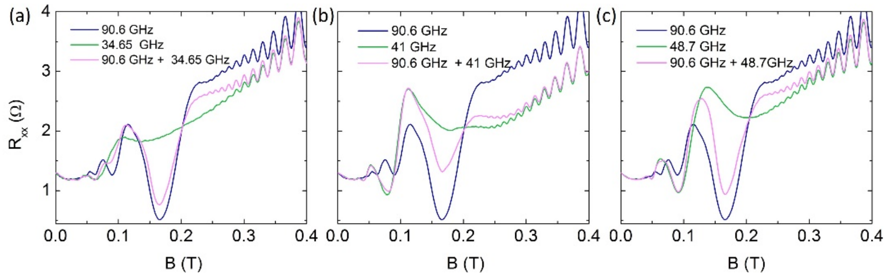

Figure 1. Monochromatic and bichromatic microwave induced magnetoresistance for high frequency f_1 = 90.6GHz and low frequency (a) f_2 = 34.65 GHz, (b) f_2 = 41.0 GHz and (c) f_2 = 48.7 GHz

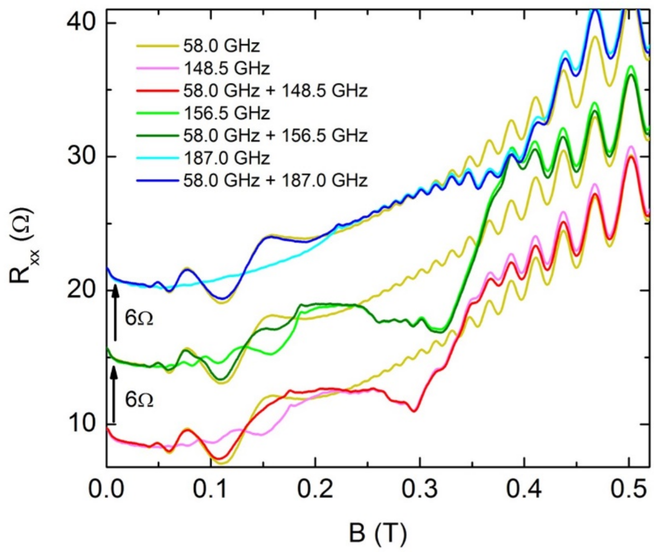

Figure 2. Monochromatic and bichromatic microwave induced oscillations in the diagonal resistance, R_{xx} for f_1 = constant = 58 GHz and f_2 = 141, 161, 174, and 207 GHz. The traces are shifted by 6Ω for clarity. The yellow solid lines show the monochromatic response of R_{xx} at 58 GHz for each case.

To further examine this behavior, the sample was also illuminated with microwave frequencies which produce R_{xx} oscillations that are further apart on the magnetic field axis such as with f_1 = 58.0GHz while f_2 = 148.5, 156.5, 187.0 GHz. The results of such measurements, shown in figure 2, indicate once again that the monochromatic low frequency R_{xx} response sets bichromatic R_{xx} response at low magnetic fields as the monochromatic high frequency R_{xx} response mostly determines the bichromatic R_{xx} response at high magnetic fields in the bichromatic experiment. .

The microwave induced magnetoresistance under bichromatic excitation with frequencies f_1 = 90.6 GHz and f_2 = 41.0GHz was also examined upon changing the microwave power, P, of the low frequency excitation at f_2; the results of such experiments are shown in Fig.3. The R_{xx} at the extrema indicated by the labels 1, 2 and 3 of Fig. 3 are plotted versus the microwave power in Fig. 4, and Fig. 4 shows a non-linear variation of the extremal resistance with P. This behavior was also observed at other frequency combinations utilized in this experiment.

2. Discussion

The bichromatic microwave response of the diagonal resistance, R_{xx} follows the low frequency monochromatic response at low magnetic fields and it deviates towards high frequency monochromatic microwave response as the magnetic field strength increases. Previous studies [24,25] had suggested that the bichromatic microwave induced magneto-resistance oscillations could be explained by averaging the two monochromatic microwave responses. This suggestion does not seem to agree with the results of this experiment since our experiment has shown that the bichromatic response depends on the magnetic field strength and the microwave frequency. Also, the bichromatic microwave R_{xx} response varies nonlinearly with the microwave power, see Fig. 4, similar to the non-linear variation observed with monochromatic microwaves.[13,21,22].

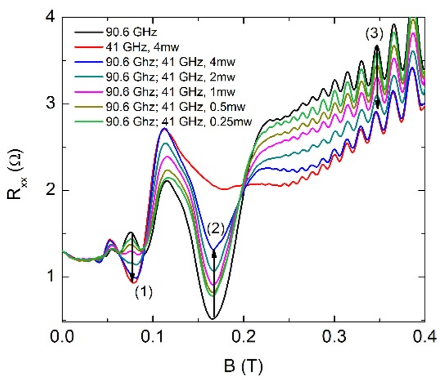

Figure 3. Monochromatic and bichromatic microwave induced magnetoresistance, R_{xx}, at frequencies 90.6 GHz and 41.0 GHz for microwave powers of 4, 2, 1, 0.5 and 0.25 microwave at the low frequency and fixed power at the high frequency. Positions (1), (2) and (3) are three extrema B-values of bichromatic R_{xx} oscillatory response.

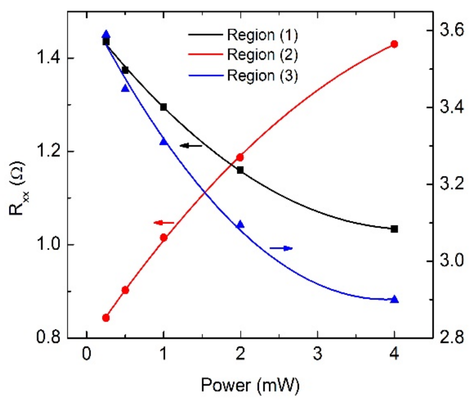

Figure 4. Microwave power variation of the diagonal resistance R_{xx} at the extremal positions 1, 2 and 3 marked in Fig. 3.

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References

[1] Mani R G, Smet J H, von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2002 *Nature (London)* **420**, 646; 2004 *Phys. Rev. Lett.* **92**, 146801; 2004 *Phys. Rev. B* **69**, 193304
[2] Mani R G, Narayanamurti V, von Klitzing K, Smet J H, Johnson W B, and Umansky V 2004 *Phys. Rev. B* **70**, 155310; 2004 *Phys. Rev. B*. **69**, 161306
[3] Mani R G, 2004 *Physica E* **22**, 1; 2004 ibid. **25**, 189
[4] Kovalev A E, Zvyagin S A ,Bowers C R, Reno J L , and Simmons J A 2004 *Solid State Commun.*

130, 379
[5] Zudov M A 2004 *Phys. Rev. B* **69**, 041304
[6] Simovic B, Ellenberger C, Ensslin K, Tranitz H P, and Wegscheider W 2005 *Phys. Rev. B* **71**, 233303
[7] Mani, R G 2005 *Phys. Rev. B* **72**, 075327; 2007 *Appl. Phys. Lett.* **91**, 132103; 2008 *Physica E* **40**, 1178
[8] Smet J.H et al. 2005 *Phys. Rev. Lett.* **95**, 116804
[9] Mani R G 2008 *Appl. Phys. Lett.* **92**, 102107
[10] Wiedmann S, Gusev G M, Raichev O E, Lamas T E, Bakarov A K and Portal J C 2008 *Phys. Rev. B.* **78**, 121301
[11] Konstantinov D and Kono K 2009 *Phys. Rev. Lett.* **103**, 266808
[12] Mani R G, Johnson W B, Umansky V, Narayanmurti V, and Ploog K 2009 *Phys. Rev. B* **79**, 205320
[13] Mani R G, Gerl C, Schmult S, Wegscheider W and Umansky V 2010 *Phys. Rev. B* **81**, 125320
[14] Ramanayaka A N, Mani R G, and Wegscheider W 2011 *Phys. Rev. B* **83**, 162303
[15] Mani R G, Ramanayaka A N, and Wegscheider W 2011 *Phys. Rev. B* **84**, 085308; Ramanayaka A N, Mani R G, Inarrea J and Wegscheider W 2012 *ibid.* **85**, 205315
[16] Mani R G, Hankinson J, Berger C and de Heer W A 2012 *Nat. Comm.* **3**, 996
[17] Mani R G, Ramanayaka A N, Ye T, Heimbeck M S, Everitt H O and Wegscheider W 2013 *Phys. Rev. B* **87**, 245308
[18] Ye T, Mani R G and Wegscheider W 2013 *Appl. Phys. Lett.* **102**, 242113; 2013 *Appl. Phys. Lett.* **103**, 192106
[19] Mani R G and Kriisa A 2013 *Sci. Rep.* **3**, 3478
[20] Mani R G, Kriisa A, and Wegscheider W 2013 *Sci. Rep.* **3**, 2747
[21] Ye T, Liu H C, Wegscheider W and Mani R G 2014 *Phys. Rev. B* **89**, 155307
[22] Ińarrea J, Mani R G and Wegscheider W 2010 *Appl. Phys. Lett.* **82**, 205321
[23] Lei X L and Liu S Y 2005 *Phys. Rev. B* **72**,075345
[24] Zudov M A, Du R R, Pfeiffer L N and West K W 2006 *Phys. Rev. Lett.* **96**, 236804
[25] Lei X L and Liu S Y 2006 *Appl. Phys. Lett.* **89**, 182117
[26] Durst A C, Sachdev S, Read N and Girvin S M 2003 *Phys. Rev. Lett.* **91**, 086803
[27] Inarrea J and Platero G 2005 *Phys. Rev. Lett.* **94**, 016806
[28] Lei X L, 2009 *Physica E* **42**, 63
[29] Andreev, A V, Aleiner I L and Millis, A J 2003 *Phys. Rev. Lett.* **91**, 056803
[30] Ryzhii V and Suris R 2003 *J. Phys. Condens. Matter* 15, 6855
[31] Koulakov A A and Raikh M E 2003 *Phys. Rev. B* **68**, 115324
[32] Ryzhii V 2003 *Phys. Rev. B* **68**, 193402
[33] Lei X L and Liu S Y 2003 *Phys. Rev. Lett.* 91, 226805
[34] Dmitriev I A, Vavilov M G, Aleiner I L, Merlin A D and Polyakov D G 2005 *Phys. Rev. B* **71**, 115316 (2005)
[35] Inarrea J and Platero G 2011 *Phys. Rev. B* **76**, 073311
[36] Chepelianskii A D, Pikovsky A S and Shepelyansky, D L 2007 *Eur. Phys. J. B* **60**, 225
[37] Finkler I G and Halperin B I 2009 *Phys. Rev. B* **79**, 085315
[38] Chepelianskii A D and Shepelyansky D L 2009 *Phys. Rev. B* **80**, 241308
[39] Mikhailov S A 2011 *Phys. Rev. B* **83**, 155303 (2011)
[40] Inarrea J 2011 *Appl. Phys. Lett.* **99**, 232115 (2011)
[41] Lei X L and Liu S L 2012 *Phys. Rev. B* **86**, 205303 (2012)
[42] Beltukov Y M and Dyakonov M I 2016 *Phys. Rev. Lett.* **116**, 176801