Evolution of the frequency-dependent polarization-angle phase-shift in the microwave radiation-induced magnetoresistance oscillations

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Abstract. We report the evolution of the phase shift, \( \theta_0 \), extracted from traces of the diagonal resistance, \( R_{xx} \), vs. the linear polarization angle, \( \theta \), at oscillatory extrema of the microwave radiation induced magnetoresistance oscillations over the \( 36 \leq f \leq 40 \) GHz band in GaAs/AlGaAs system. A reference phase shift for the linear polarization angle in the vicinity of the specimen is obtained with the help of a sensitive carbon resistor. We fit an empirical cosine square law to the sinusoidal responses of \( R_{xx} \) vs. \( \theta \) to extract the phase shift \( \theta_0 \). The quasi-continuous variation \( \theta_0 \) vs. \( f \) trace suggests a preferable polarization orientation for the specimen, and the \( f \) - and \( B \) -independence of overall average of \( \theta_0 \).

1. Introduction
Microwave radiation-induced zero-resistance states and associated magnetoresistance oscillations (MRIMOs)[1, 2], which appear in the 2D electron system subjected to crossed electric and magnetic fields, have revealed a "1/4-cycle phase-shift" in its periodicity in \( 1/B \) along with a multitude of interesting properties after nearly a decade research[3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. At the same time, a number of theoretical works have attempted to provide plausible explanations of MRIMOs[20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35], based on the displacement model[22, 25], the nonparabolicity model[23], the inelastic model[26] and the radiation-driven electron-orbit model[24, 27].

Recently, the sensitivity of the amplitude of MRIMOs to linearly polarized radiation polarization was reported[12, 14, 18]. The results demonstrated a sinusoidal variation in the amplitude of the oscillatory magnetoresistance with microwave polarization angle at moderate radiation power. This sinusoidal variation can be described by an empirical cosine square function, \( R_{xx}(\theta) = A \pm C \cos^2(\theta - \theta_0) \), where \( R_{xx} \) is diagonal magnetoresistance, \( \theta \) is microwave polarization angle, \( \theta_0 \) is phase shift, and the plus and minus signs correspond to the oscillatory maxima and minima, respectively. Previous works examined the dependence of \( \theta_0 \) on microwave frequency, \( f \), and \( B \) at a set of discrete frequencies. In this approach, however, the evolution of \( \theta_0 \) between the measured \( f \) was unknown. In this report, therefore, the quasi-continuous evolution of the phase shift \( \theta_0 \) extracted from \( R_{xx} \) vs. \( \theta \) traces of the radiation-induced magnetoresistance oscillations at a set of six oscillatory extrema, and the reference phase shift reported by a
Figure 1. (Color online) (a) This schematic shows relative device arrangement of GaAs/AlGaAs heterojunction and the carbon resistor (ABR) subjected to rotatable linearly polarized radiation. The polarization angle, $\theta$, is defined with respect to Hall bar axis clockwise. Diagonal voltage, $V_{xx}$, is collected via four-terminal lock-in technique. (b) The trace of $R_{xx}$ vs. $B$ shows strong MRIMOs at $f = 38$ GHz. The oscillatory extrema of MRIMOs are assigned to $P_{1+}$, $V_{1+}$, $P_{2+}$, $P_{2-}$, $V_{1-}$, and $P_{1-}$ respectively over $36 \leq f \leq 40$ GHz band.

sensitive carbon resistor, are examined over the frequency band $36 \leq f \leq 40$ GHz for Hall-bar section. The results indicate that $\theta_0$ results from the intrinsic response of specimen and the overall average of $\theta_0$ is independent upon $f$ and $B$.

2. Experiment and Results

Magnetotransport in 200-µm-wide Hall-bar type GaAs/AlGaAs heterojunction devices with electron density $n = 3.3 \times 10^{11} \text{cm}^{-2}$ and mobility $\mu = 14 \times 10^{6} \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ at $T = 1.5K$ were measured using the four-terminal lock-in technique. The diagonal voltage, $V_{xx}$, was collected vs. the polarization angle, $\theta$, which is defined as the angle between the Hall bar axis and linear-polarized microwave electric field as in Fig. 1(a). A carbon resistance sensor with a strong negative temperature coefficient, i.e., $dR_{ABR}/dT \leq 0$, at liquid helium temperatures, i.e., an Allen-Bradley resistor (ABR), was placed next to the Hall bar specimen for the sake of in-situ measurement of $\theta_0$ and the independent detection of microwave polarization rotation at the sample location. Typical MRIMOs in $R_{xx}$ vs. $B$ at $f = 38$ GHz are shown in Fig. 1(b). We define the first (second) peak and the first valley on the positive side of $B$ as $P_{1+}$ ($P_{2+}$) and $V_{1+}$ respectively. Likewise, $P_{1-}$, $V_{1-}$ and $P_{2-}$ are labels utilized to identify extrema on the negative side of the $B$ axis. For the $R_{xx}$ vs. $\theta$ measurements, we swept $f$ from 36 to 40 GHz with the polarization angle held constant between $0^\circ \leq \theta \leq 360^\circ$ at $10^\circ$ intervals.

To rule out the possibility that the $\theta_0$ observed in the specimen is due to uncharacterized incident polarization rotation, the carbon resistor (ABR) serves as a radiation polarization sensor to determine the polarization orientation near the sample. Fig. 2(a) displays normalized $R_{ABR}$ color plot of $f$ vs. $\theta$ over $36 \leq f \leq 40$ GHz with $0^\circ \leq \theta \leq 360^\circ$ at $V_{1-}$. High normalized $R_{ABR}$ occurring near $0^\circ$ matches our expectations for the incident microwave polarization. A nice sinusoidal curve of normalized $R_{ABR}$ vs. $\theta$ at $f = 38.3$ GHz is fit to the empirical cosine square function to extract $\theta_{0,ABR}$; see Fig. 2(b). The extracted $\theta_0$ over $36 \leq f \leq 40$ GHz are
Figure 2. (Color online) This figure shows the normalized $R_{ABR}$ (left color plot: a) and $R_{xx}$ (right color plot: d) over $36 \leq f \leq 40 \text{ GHz}$ band with $0^\circ \leq \theta \leq 360^\circ$ at V1−. Panel (b) and (e) illustrate nice sinusoidal variation in normalized resistance fit to the empirical cosine square function with $\theta$ at given $f$. Panel (c) and (f) demonstrate the plot of $f$ vs. $\theta_0$ with the average $\theta_0$, which are extracted from the fit at each $f$. The figure (c) and (f) imply a constant average phase shift at V1−.

plotted in Fig 2(c) with an average $\theta_{0,ABR}$ indication at $5.3^\circ$ (red dashed line), which proves that the incident microwave polarization orientation has not changed near the specimen. Similarly, Fig. 2(d) exhibits normalized $R_{xx}$ color plot of $f$ vs. $\theta$. Then, we fit cosine square function to the sinusoidal curve of normalized $R_{xx}$ vs. $\theta$ (Fig. 2(e)) to obtain $\theta_0$ within $36 \leq f \leq 40 \text{ GHz}$ with average $\theta_0 = -41.3^\circ$ (Fig. 2(f)). Clearly, the average $\theta_0$ shows a recognizable difference with respect to $\theta_{0,ABR}$.

3. Discussion

Although the microwave launcher and the Hall bar axis were pre-aligned before carrying out the magnetotransport measurements in previous microwave polarization angle dependence studies with the aid of a microwave power detector, there remained the possibility that the observed $\theta_0$ was due to the reflection caused by metallic contacts and bonded gold wires. However, the response to incident microwaves reported by the carbon resistor collected here simultaneously with magnetotransport measurements suggests that the average $\theta_{0,ABR}$ is extremely similar to the standard error obtained by microwave power detector in the prealignment process. This feature affirms that the observed $\theta_0$ results from intrinsic sample properties. Plus, according to the average $\theta_0$ examined at remaining oscillatory extrema, which are all located at $\approx -42^\circ$ (not shown here), while the extracted $\theta_{0,ABR}$ and $\theta_0$ manifest similar standard errors, the average $\theta_0$ is independent upon $f$ and $B$. Thus, our results imply that the GaAs/AlGaAs Hall-bar device possesses an intrinsic preferred polarization orientation to incident microwaves.

4. Conclusion

We suggest here that the $\theta_0$ is an intrinsic property of the GaAs/AlGaAs 2D specimen with the help of a sensitive carbon resistor. In addition, the similar average $\theta_0$ values examined at different oscillatory extrema suggest that the average $\theta_0$ is independent of $f$ and $B$, and the sample exhibits a preferred polarization orientation to incident microwaves.
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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
[2] Zudov M A, Du R R, Pfeiffer L N and West K W 2003 Phys. Rev. Lett. 90 046807
[3] Mani R G, Narayanamurti V, von Klitzing K, Smet J H, Johnson W B and Umansky V 2004 Phys. Rev. B 69 161306(R); 2004 Phys. Rev. B 70 155310
[4] Mani R G, Smet J H, von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2004 Phys. Rev. Lett. 92 146801; 2004 Phys. Rev. B 69 193304
[5] Mani R G 2004 Physica E (Amsterdam) 22 1-6; 2004 Physica E Amsterdam 25 189-197; 2004 Int. J. Mod. Phys. B 18 3473-3480; 2004 Appl. Phys. Lett. 85 4962-4964; 2004 Phys. Rev. B 72 075327; 2007 Appl. Phys. Lett. 91 132103; Solid State Comm. 2007 144 409-412; 2008 Physica E (Amsterdam) 40 1178-1181
[6] Smet J H, Gorshunov B, Jiang C, Pfeiffer L, West K, Umansky V, Dressel M, Meisels R, Kuchar F and von Klitzing K 2005 Phys. Rev. Lett. 95 116804
[7] Studenikin S A, Sachrajda A S, Gupta J A, Wasilewski Z R, Fedorych O M, Byszewski M, Maude D K, Potemski M, Hilke M, West K W and Pfeiffer L N 2007 Phys. Rev. B 76 163321
[8] Raichev O E 2008 Phys. Rev. B 78 125304
[9] Mani R G, Johnson W B, Umansky V, Narayanamurti V and Ploog K 2009 Phys. Rev. B 79 205320
[10] Fedorych O M, Potemski M, Studenikin S A, Gupta J A, Wasilewski Z R and Dmitriev I A 2010 Phys. Rev. B 81 201302(R)
[11] Wiedmann S, Gusev G M, Raichev O E, Bakarov A K and Portal J C 2010 Phys. Rev. Lett. 105 026804
[12] Mani R G, Ramanyayaka A N and Wegscheider W 2011 Phys. Rev. B 84 085308
[13] Bogan A, Hatke A T, Studenikin S A, Sachrajda A, Zudov M A, Pfeiffer L N and West K W 2012 Phys. Rev. B 86 235305
[14] Ramanyayaka A N, Mani R G, Ihara J and Wegscheider W 2012 Phys. Rev. B 85 205315
[15] Mani R G, Ramanyayaka A N, Ye T, Heinbeck M S, Everitt H O and Wegscheider W 2013 Phys. Rev. B 87 245308
[16] Konstantinov D, Monarkha Y and Kono K 2013 Phys. Rev. Lett. 111 266802
[17] Ye T, Liu H-C, Wegscheider W and Mani R G 2014 Phys. Rev. B 89 155307
[18] Liu H-C, Ye T, Wegscheider W and Mani R G 2015 J. Appl. Phys. 117 064306
[19] Ye T, Liu H-C, Wang Z, Wegscheider W and Mani R G 2015 Sci. Rep. 5 14880
[20] Durst A C, Sachdev S, Read N and Girvin S M 2003 Phys. Rev. Lett. 91 086803
[21] Ryzhii V and Suris R 2003 J. Phys. Cond. Matt. 15 6855
[22] Lei X L and Liu S Y 2003 Phys. Rev. Lett. 91 226805
[23] Koulakov A A and Raikh M E 2003 Phys. Rev. B 68 115324
[24] Ihara J and Platero G 2005 Phys. Rev. Lett. 94 016806
[25] Lei X L and Liu S Y 2005 Phys. Rev. B 72 075345
[26] Dmitriev I A, Vavilov M G, Aleiner I L, Mirlin A D and Polyakov D G 2005 Phys. Rev. B 71 115316
[27] Ihara J and Platero G 2005 Phys. Rev. B 76 075311
[28] Wang S and Ng T-K 2008 Phys. Rev. B 77 165324
[29] Ihara J, Mani R G and Wegscheider W 2010 Phys. Rev. B 82 205321
[30] Mikhailov S A 2011 Phys. Rev. B 83 155303
[31] Chepelianskii A D, Iadjet J, Farrer I, Beere H E, Ritchie D A and Bouchiat H 2012 Phys. Rev. B 86 205108
[32] Lei X L and Liu S Y 2015 Phys. Rev. B 86 205303
[33] Zhirov O V, Chepelianskii A D and Shepelyansky D L 2013 Phys. Rev. B 88 035410
[34] Yar A and Sabeeh K 2015 J. Phys.:Cond. Matt. 27 435007
[35] Ibarra-Sierra V G, Sancho-Santa J C, Cardoso J L and Kunold A 2015 Annal. Phys. 362 83