Extraction of overlapping radiation-induced magnetoresistance oscillations and bell-shaped giant magnetoresistance in the GaAs/AlGaAs 2DES using a multiconduction model

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Abstract. We present an experimental study aimed at extracting the microwave radiation-induced magnetoresistance oscillations from the bell-shape giant magnetoresistance in high mobility GaAs/AlGaAs devices using a multi-conduction model. The results show that the multi-conduction model describes the observed giant magnetoresistance effect and the model helps to extract radiation-induced magnetoresistance oscillations, over a wider parameter space.

1. Introduction

Interest in the GaAs/AlGaAs heterostructure two-dimensional electron systems (2DES) has been motivated by the enhanced physical and electrical properties of this system, including 2D electron mobilities well above $10^7$ cm²/Vs. This 2DES shows interesting physical phenomena such as novel microwave induced zero-resistance states and associated radiation-induced magnetoresistance oscillations, [1-14] and Giant Magneto-Resistance (GMR) [14-18]. Photo-excited magnetotransport has been studied over the past decade, while negative GMR, which is proportional to the square of magnetic field, $B^2$, has been known since the initial report in 1983 [15]. Studies of negative GMR have revealed the influence of various factors [15-18]. Typically, the bell-shape negative GMR effect is fit with a parabolic magnetic-field-dependence ($B^2$-fit) model [17,18]. However, from the experimental perspective, there is more to the bell-shape negative GMR than the initial parabolic term.

In this study, we examine the overlap of microwave induced magnetoresistance oscillations with the bell-shape positive and negative-GMR in GaAs/AlGaAs 2DES. The aim of this study is to develop a technique to separate coexisting GMR and microwave induced magnetoresistance oscillations’s and extract associated features. We utilized the multi-conduction model to fit the GMR effect [16]. Subtracting the multi-conduction fit results from the experimental data helps to isolate the microwave induced magnetoresistance oscillations.

2. Experimental

Electrical measurements were carried out at $T \leq 1.7$ K using low frequency lock-in-based techniques on a 2DES with mobility and electron density of $10^7$ cm²/V s and $2.4 \times 10^{11}$ cm² respectively. Both a constant $I_{dc} = 2$ μA and a variable $I_{ac}$ were applied along the Hall bar direction. The magnetoresistance $R_{ac} = V_{ac}/I_{ac}$. Microwaves at frequency $f = 70.1 \text{GHz}$ were conveyed to the sample via a waveguide.

3. Results and Data fit

The solid lines of Fig. 1(a) exhibit the $R_{ac}$ vs. $B$ at 1.7 K under microwave excitation at $f = 70.1 \text{ GHz}$. Microwave induced magnetoresistance oscillations are evident in the range $-0.2 < B < 0.2$ Tesla. In...
addition, a close study of the data reveals sharp negative-magnetoresistance in the range of $-0.01 \leq B \leq 0.01$ Tesla, with a peak at $B=0$ Tesla, which looks like the weak-Localization (WL) effect [19,20]. Above 0.05 T, Fig. 1(a) shows positive magnetoresistance. In Fig. 1 (a), the amplitude of the microwave induced magnetoresistance oscillations decreases with decreasing MW power. Figure 1(b) illustrates that the amplitude of microwave induced magnetoresistance oscillations decreases with increasing $I_{dc}$. Also, a large bell-shaped negative GMR develops with increasing $I_{dc}$. The WL-peak is unaffected by either $P$ or $I_{dc}$.

In order to extract microwave induced magnetoresistance oscillations from the overlapping magnetoresistive effects, we introduced a fitting model that addresses the WL-effect and the bell-shaped GMR effect. Weak localization effect is modelled using the 2D WL theory by neglecting spin-orbit and spin scattering [19-20]. The bell-shape negative GMR effect is addressed with the multi-conduction model [16]. To account for the experimentally observed bell-shape GMR, an additional conductivity term described by conductivity, $\sigma_i$ and mobility, $\mu_i$ is introduced to the multi-conduction model, eqns. 3 and 4 in Ref 16. Thus, the total diagonal conductivity, $\sigma_{xx}$ and off-diagonal conductivity, $\sigma_{xy}$ are given as follows,

$$\sigma_{xx} = \left\{ \frac{\sigma_0}{1 + (\mu_0 B)^2} \right\} + \left\{ \frac{\sigma_1}{1 + (\mu_1 B)^2} \right\} \quad (1)$$

$$\sigma_{xy} = \left\{ \frac{\sigma_0 \mu_0 B}{1 + (\mu_0 B)^2} \right\} + \left\{ \frac{\sigma_1 \mu_1 B}{1 + (\mu_1 B)^2} \right\} \quad (2)$$

The zeroth conductivity terms, in eqns. (1) and (2) represents the high mobility electrons in 2D-electron system, thus $\sigma_0 = n_0 e \mu_0$ where $n_0$, electron density and $\mu_0$, electron mobility of the 2DES. The number of free parameters in the fit model has been reduced to two, by holding constant the values of $n_0$ and $\mu_0$, respectively.

Figure 1. This panel exhibits the $R_{xx}$ vs. $B$ (solid lines) under photo-excitation at $f = 70.1$ GHz, at $T = 1.7$ K, also shown are the fits (dashed-lines) to the data using multi-conduction model, see text. 

a) Exhibits the $R_{xx}$ at various MW-powers, $P$ ranging from 0.1 mW to 0.8 mW, at $I_{dc} = 0$ $\mu$A. Insert shows the fit extracted $\sigma_i$ as a function of $P$. b) Exhibits the $R_{xx}$ at different $dc$-bias, $I_{dc}$ from 0 $\mu$A to 20 $\mu$A, the insert illustrates the fit extracted $\sigma_i$ as a function of $I_{dc}$. 

![Figure 1](image-url)
Dashed lines in Fig. 1 exhibit the fitting results to the experimental data. Also, fit extracted $\mu_i = 1.9 \times 10^5$ cm$^2$/V s is unaffected by $P$ in Fig. 1(a). However, the fit result shows $I_{dc}$ dependency of $\mu_i$: as $I_{dc}$ changes from 0 µA to 20 µA, $\mu_i$ increases from 1.9 to 6.2 x 10$^4$ cm$^2$/V s.

Insets in Fig. 1 exhibit the fit extracted additional conductivity term $\sigma_i$, which captures the bell-shape GMR effect observed in the experimental data. As shown in Fig. 1(a) (inset), the $\sigma_i$ is not significantly affected by the applied $P$, however, it slightly decreases at higher power. In contrast, in Fig. 1(b) (inset), the $\sigma_i$ shows significant change as a function of $I_{dc}$. One can observe a clear transition of $\sigma_i$ from positive to a negative value with increasing dc-bias from 0 µA to 20 µA. The transition occurs in the range of 10 µA < $I_{dc}$ < 12 µA.

![Figure 2](image)

**Figure 2.** This figure shows the extracted microwave induced magnetoresistance oscillations, $\Delta R_{xx}$, after subtracting the fit results from the experimental data, in the positive magnetic field. a) Exhibits the influence of power, $P$ on the microwave induced magnetoresistance oscillations, b) Exhibits the effect of $I_{dc}$ on the microwave induced magnetoresistance oscillations, at given conditions as indicated.

In Figure 2, $\Delta R_{xx}$ is obtained by subtracting the GMR fit results from the experimental data. One can observe clear microwave induced magnetoresistance oscillations without indication of other magnetoresistance effects. In Fig. 2(a), the height of the microwave induced magnetoresistance oscillations peak indicated by arrow (↑) has decreased by about 80% upon reducing the MW-power by a factor of eight. On the other hand, as shown in Fig. 2(b), the microwave induced magnetoresistance oscillations peaks disappear at $I_{dc} = 20$ µA. Also, the peaks do not show any phase shift as a function of either MW-power or dc-bias.

### 4. Discussion

Magnetoresistance in the 2DES, under the photo-excitation and applied dc-bias, over the examined magnetic field range can arise from a number of mechanisms such as the weak localization effect, microwave-induced magnetoresistance oscillations, and bell-shape GMR. One might also examine the interplay of these effects with an applied $I_{dc}$. The weak localization effect observed at low magnetic fields is mainly a low-temperature disorder induced effect [16,19,20]. On the other hand, microwave radiation-induced magnetoresistance oscillations have been studied as a function of radiation frequency, power, polarization angle, etc. [1-14]. Studies report a nonlinear growth of microwave induced magnetoresistance oscillations with the radiation power $P$ [11]. In this study, we found an increase in microwave induced magnetoresistance oscillations amplitude as a function of the microwave power by examining the $\Delta R_{xx}$ obtained by subtracting the fit result from the $R_{xx}$. Experimental studies have reported the effect of an applied $I_{dc}$, and the interplay of dc-bias and microwaves in the magneto transport of GaAs/AlGaAs 2DES [22-24]. In this study, quenching of microwave induced magnetoresistance oscillations was observed at about $I_{dc} = 20$ µA. Our results
indicate a non-linear behaviour in the fit extracted $\sigma_t$. Also, bell-shape GMR effect, parameterized by $\sigma_t$, varies from positive to negative value as a function of dc-bias.

5. Conclusion

In summary, this study has shown that the multiconduction model along with weak-localization term provides a good fit to the non-oscillatory experimental data, as it also captures the essential features in bell-shape GMR effect, over various experimental parameters. In addition, the model serves to extract coexisting effects such as, radiation induced magnetoresistance oscillations, from the bell-shape GMR.

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