Magnetotransport excited by linearly polarized radiation in 2D electron systems

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Abstract. We have studied the influence of the polarization angle of linear radiation on the recently measured radiation-induced magnetoresistance oscillations in two-dimensional electron systems. We have applied a previous theoretical framework based in solving the Schrödinger equation of a two-dimensional quantum oscillator subjected to a time-varying force. In agreement with experimental results we have obtained that the magnetoresistance is not affected by the orientation of the electric field of linearly polarized radiation.

1. Introduction

In the recent years basic and applied research have focussed on the study of optical and transport properties of low dimensional systems[1]. As a result, important and unusual properties have been discovered when, for instance, two-dimensional electron systems (2DES) are subjected to external AC or DC fields. We can highlight the recently measured effect of microwave-induced resistance oscillations (MIRO)[2, 3, 4] and zero resistance states (ZRS)[2, 3]. These experiments obtain similar MIRO when radiation is linearly polarized either in the transport direction or perpendicular to it. Furthermore, other experiments obtain that the longitudinal magnetoresistivity response $\rho_{xx}$ is independent of the direction of the circular polarization of MW radiation[5]. Some theoretical contributions[6, 7, 8, 9, 10, 11, 12, 13, 14, 15] have been presented trying to explain such striking effects. In this paper we present a theoretical model to treat the physical problem of a 2DES subjected simultaneously to a static, moderate and uniform magnetic field ($B$) and microwave radiation (MW)[6, 16, 17] linearly polarized at any angle.

2. Theoretical model

We consider a 2DES ($x - y$ plane) subjected to a perpendicular ($z$ direction), static $B$, a DC electric field $E_{dc}$, responsible of the electron transport through the sample ($x$ direction). The system is also subjected to linearly polarized MW radiation. The electric field $\vec{E}(t)$ of MW can be in different polarization angles ($\alpha$) (see Fig. 1). This field is given by: $\vec{E}(t) = (E_{0x} \hat{i} + E_{0y} \hat{j}) \cos wt$ where $E_{0x}, E_{0y}$ are the amplitudes of the MW field and $w$ the frequency. Thus, $\alpha$ is given by $\tan \alpha = \frac{E_{0y}}{E_{0x}}$. Considering the symmetric gauge for the vector potential of $B$, $\vec{A}_B = -\frac{1}{2} \vec{r} \times \vec{B}$ the corresponding Hamiltonian reads:
Figure 1. Schematic diagram showing a 2DEG illuminated by linearly polarized MW radiation at different polarization angles ($\alpha$). a) $\alpha = 0$: the MW electric field is aligned to the transport direction ($x$ direction). b) $0 < \alpha < \pi/2$. c) $\alpha = \pi/2$: the MW electric field is perpendicular to $x$.

$$H = \frac{p_x^2 + p_y^2}{2m^*} + \frac{w_c}{2} L_z + \frac{1}{2} m^* \left[ \frac{w_c}{2} \right]^2 \left[ (x - X)^2 + y^2 \right]$$

$$- \frac{e^2 E_0^2}{2m^* \left[ \frac{w_c}{2} \right]^2} x - eE_0 x \cos wt - eyE_0 y \cos wt - eE_0 X \cos wt$$

$X = \frac{eE_0}{m^*(w_c/2)^2}$ is the center of the orbit for the electron cycloidal motion, $w_c$ is the cyclotron frequency, $L_z$ is the $z$-component of the electron total angular momentum. The analytic solution of the Hamiltonian $H$ can be obtained[6, 16, 17]:

$$\Psi(x, y, t) = \phi_N [(x - X - a(t)), (y - b(t)), t] \times \exp \frac{i}{\hbar} \left[ m^* \left( \frac{da(t)}{dt} x + \frac{db(t)}{dt} y \right) + \frac{m^* w_c (b(t) x - a(t) y)}{2} - \int_0^t Ldt' \right] \times \sum_{p=-\infty}^{\infty} J_p(A_N)e^{ipt}$$

(1)

where $J_p$ are Bessel functions with arguments, $A_N[18]$, $\phi_N$ the well-known Fock-Darwin states[19] and $L$ the classical Lagrangian. The expression for $a(t)$ and $b(t)$ can be also obtained for an arbitrary angle $\alpha$,[6, 12]:

$$a(t) = \frac{eE_0 \cos wt}{m^* \sqrt{w^2(w^2 - w_c^2)^2 + \gamma^4}} = A \cos wt$$

(2)

$$b(t) = \frac{eE_0 \sin wt}{m^* \sqrt{w^2(w^2 - w_c^2)^2 + \gamma^4}}$$

(3)
\( \gamma \) is a material and sample-dependent damping factor which dramatically affects the movement of the MW-driven electronic orbits[18]. Along with this movement interactions occur between electrons and lattice ions, yielding acoustic phonons and producing a damping effect in the electronic motion. We have developed a microscopical model[12] to calculate \( \gamma \), estimating a numerical value of \( \gamma \simeq 10^{12} \text{s}^{-1} \) for GaAs. The obtained expressions for \( a(t) \) and \( b(t) \) together with the expression of the total wave function, imply that due to the MW radiation, the center position of electronic orbits are not fixed and performs a circular motion in the \( x-y \) plane. This motion is reflected in the \( x \) direction as harmonic oscillatory with the MW frequency \( w \).

Now we introduce the scattering suffered by the electrons due to charged impurities randomly distributed in the sample[20, 12]. Firstly we calculate the electron-charged impurity scattering rate \( 1/\tau \), and secondly we find the average effective distance advanced by the electron in every scattering jump: \( \Delta X^{MW} = \Delta X^0 + A \cos w \tau \) where \( \Delta X^0 \) is the effective distance advanced when there is no MW field present. Finally the longitudinal conductivity \( \sigma_{xx} \) can be calculated: 
\[
\sigma_{xx} \propto \int dE \frac{\Delta X^{MW}}{\tau} (f_i - f_f),
\]
where \( f_i \) and \( f_f \) the corresponding distribution functions for the initial and final Landau states respectively and \( E \) is the energy. To obtain \( \rho_{xx} \) we use the relation
\[
\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx \frac{\sigma_{xx}}{\sigma_{xy}^2}, \quad \text{where} \quad \sigma_{xy} \simeq \frac{n_i e B}{1} \quad \text{and} \quad \sigma_{xx} \ll \sigma_{xy}.
\]

3. Results
According to our model, the \( \rho_{xx} \) response under MW excitation is governed by the term \( A \cos w \tau \): 
\[
\rho_{xx} \propto A \cos w \tau.
\]
Therefore we would expect different results of \( \rho_{xx} \) depending on the angle \( \alpha \) since \( \rho_{xx} \) depends on \( \alpha \) through the amplitude \( A \). However if the damping factor \( \gamma \) is larger
than the MW frequency, $\gamma > w$, $\gamma$ would become the leading term in the denominator of $A$. In this situation, $\gamma$ is able to quench the influence of the other terms. Therefore similar values are obtained for the amplitude of the orbit center for different $\alpha$. For GaAs and typical experimental MW frequencies\cite{21, 22}, a value for $\gamma$ about $1 - 2 \times 10^{12} \text{s}^{-1}$ is enough to obtain a similar $\rho_{xx}$ response irrespective of the value of $\alpha$. In Fig.2 we show the calculated $\rho_{xx}$ as a function of $B$ for linearly polarized radiation and for different polarization angles. MW frequency $w = 90 \text{ GHz}$. $\rho_{xx}$ response is practically immune to the polarization angle, specially for $B$ below cyclotron resonance (see vertical dashed line, Fig. 2a).

4. Conclusions

In conclusion, we have studied the experimental result of immunity of 2DES $\rho_{xx}$ oscillations excited by linearly polarized MW. Different values of polarization angles are considered from parallel to the transport direction to perpendicular to it. In agreement with experiments we show that, under strong enough damping, the $\rho_{xx}$ response is totally immune to the different orientations of the electric field of linearly polarized MW.

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6. References

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