Terahertz-induced resistance oscillations in high mobility two-dimensional electron systems.

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We report on a theoretical work on magnetotransport under terahertz radiation with high mobility two-dimensional electron systems. We focus on the interaction between the obtained radiation-induced magnetoresistance oscillations (RIRO) and the Shubnikov-de Haas (SdHO) oscillations. We study two effects experimentally obtained with this radiation. First, the observed disappearance of the SdHO oscillations simultaneously with the vanishing resistance at the zero resistance states region. And secondly the strong modulation of the SdHO oscillations at sufficient terahertz radiation power. We conclude that both effects share the same physical origin, the interference between the average advanced distance by the scattered electron between irradiated Landau states, (RIRO), and the available initial density of states at a certain magnetic field, (SdHO). Thus, from a physical standpoint, what the terahertz experiments and theoretical simulations reveal is, on the one hand, the oscillating nature of the Landau states subjected to radiation and, on the other hand, how they behave in the presence of scattering.

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One of the most striking effects discovered in the last decade regarding radiation-matter coupling is the microwave-induced magnetoresistance ($R_{xx}$) oscillations (MIRO)\textsuperscript{15,22}. This effect shows up in high mobility two-dimensional electron systems (2DES) when they are irradiated with microwaves (MW) at low temperature ($T \sim 1$K) and under low magnetic fields ($B$) perpendicular to the 2DES. Peaks and valleys of MIRO increase with MW power ($P$) but the latter end up into zero resistance states (ZRS)\textsuperscript{22} at high enough $P$. If these effects, MIRO and ZRS, can be qualified as striking, it is even more remarkable that after more than ten years of important experimental\textsuperscript{16–18} and theoretical efforts\textsuperscript{19–21}, their physical origin still remains controversial and far from reaching a definite consensus among the scientists devoted to this field. In this way, the two generally "accepted" theoretical models explaining MIRO, (displacement\textsuperscript{24} and inelastic\textsuperscript{25} models) are completely under question because they are not able to explain either recent experimental result\textsuperscript{34,35} or the basic features of MIRO. Among the different features describing MIRO, three of them deserve to be highlighted: first, they are periodic in $B^{-1}$; second, the oscillations minima present a 1/4 cycle phase shift and third, the dependence of MIRO on MW power follows a sublinear relation (square root). Thus, other theoretical approaches are calling to take over and play a role trying to explain the different special properties and physics of MIRO and ZRS\textsuperscript{19,20,25}.

In this paper we report on a theoretical work on magnetotransport in high mobility two-dimensional electron systems under a higher radiation frequency than microwaves: terahertz (TH) radiation. We focus on the interaction between the obtained radiation-induced magnetoresistance oscillations (RIRO) and the Shubnikov-de Haas (SdHO) oscillations. The terahertz band offers the possibility of studying this interaction because both kind of oscillations coexists while MIRO tend to vanish when the SdHO are more intense and the effects of interaction are more difficult to observe. We first recover the basic or universal signature of radiation-induced resistance oscillations: periodicity in in $B^{-1}$, the 1/4 cycle phase shift\textsuperscript{34,36} and the sublinear radiation power dependence\textsuperscript{14,16}. Then, we study two new effects experimentally obtained with TH, first the observed disappearance of the SdHO oscillations simultaneously with the vanishing resistance on the zero resistance region\textsuperscript{37,38}. And secondly the strong modulation of the SdHO oscillations at sufficient TH radiation power\textsuperscript{39,40}. The theoretical contribution of this paper is based on the radiation-driven electron orbits model\textsuperscript{19–21}. This model was proposed to study the magnetoresistance of a 2DES subjected to MW at low $B$ and temperature, $T$\textsuperscript{19,20,40–42}. According to this model, when a Hall bar is illuminated, the guiding centers of the Landau states perform a classical trajectory consisting in a harmonic motion along the direction of the current. Thus, the electron orbits move in phase and harmonically with each other at the radiation frequency, altering dramatically the scattering conditions and giving rise eventually to MIRO and, at higher $P$, ZRS. By using this model, the main result we obtain is that these effects are produced by a common origin, the interplay of the average advanced scattering distance by the electrons and the initial density of Landau states available at a fixed $B$.

As we said above, the radiation-driven electron orbits model was developed to analyze the longitudinal magnetoresistance of a 2DES subjected to radiation\textsuperscript{19,20,40–42}. Thus, according to this theory, the corresponding time-dependent Schrödinger equation can be exactly solved and the solution for the total wave function\textsuperscript{19,20,40–42} reads: $\Psi_n(x,t) \propto \phi_n(x-x_0-x_d(t),t)$, where $\phi_n$ is the solution for the Schrödinger equation of the unforced quantum harmonic oscillator. Thus, the obtained wave function (Landau state or Landau orbit) is...
oscillator where the guiding center of the Landau state, the same as the one of the standard quantum harmonic oscillator where the guiding center of the Landau state, $X_0$ without radiation, is displaced by $x_{cl}(t)$. $x_{cl}(t)$ is the classical solution of a negatively charged, forced and damped, harmonic oscillator,\cite{43,44},

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

(1)

where $E_0$ is the amplitude of the radiation electric field and $\beta$ is a phase constant. $\beta$ is the phase difference between the radiation-driven guiding center and the driving radiation. $\gamma$ is a phenomenologically-introduced damping factor for the interaction of electrons with the lattice ions giving rise to the emission of acoustic phonons. For high-mobility 2DES\cite{45}, $\beta \rightarrow \frac{\pi}{2}$, then, the time-dependent guiding center is, $X(t) = X_0 + x_{cl}(t) = X_0 - A \sin wt$. This physically implies that the orbit guiding centers oscillate harmonically at the radiation frequency, $w$.

To calculate the longitudinal conductivity $\sigma_{xx}$ in the 2DES we use the Boltzmann transport theory. With this theory and within the relaxation time approximation $\sigma_{xx}$ is given by the following equation,\cite{46,47}:

$$\sigma_{xx} = 2e^2 \int_0^\infty dE \rho_i(E)(\Delta X)^2 W_I \left(-\frac{df(E)}{dE}\right)$$

(2)

being $E$ the energy and $\rho_i(E)$ the density of initial Landau states (LS). $W_I$ is the remote charged impurity scattering rate, given, according to the Fermi’s Golden Rule, by $W_I = \frac{2\pi}{\hbar} | \Psi_i | V_s | \Psi_f |^2 \delta(E_f - E_i)$, where $E_i$ and $E_f$ are the energies of the initial and final LS. $\Psi_i$ and $\Psi_f$ are the wave functions corresponding to the initial and final LS respectively. $V_s$ is the scattering potential for charged impurities.\cite{48} $\Delta X$ is the average distance advanced by the electron between orbits in every scattering jump in the $x$ direction and is given by, $\Delta X = \Delta X^0 - A \sin(2\pi \frac{X_0}{b})$. $\Delta X^0$ is the advanced distance without radiation.
RIRO's, first bracket, and the SdHO, second bracket. With this expression we want to stand out the terms that use the well-known tensorial relation three different radiation powers: in panel a) $P = 0.7 mW$, in panel b) $P = 2.7 mW$ and in panel c) $P = 6.0 mW$. The remarkable result is that SdHO turn out to be modulated by the presence of radiation, being the modulation harmonic and periodic in $1/B$ and completely in phase with RIRO.

After some algebra we get to an expression for $\sigma_{xx}$:

$$\sigma_{xx} = \frac{2e^2m^*}{\pi\hbar^2}(\Delta X)^2 W_f \left[ 1 + \frac{2X_s}{\sinh(X_s)} e^{-\frac{2\pi}{\hbar c}} \cos \left( \frac{2\pi E_F}{\hbar w_c} \right) \right]$$

where $X_s = \frac{2\pi^2k_BT}{\hbar w_c}$, $\Gamma$ is the Landau level width and $E_F$ the Fermi energy. To find the expression for $R_{xx}$ we use the well-known tensorial relation $R_{xx} = \frac{\sigma_{xx}}{\sigma_{xy}} \approx \frac{\sigma_{xx}}{\sigma_{xy}}$, where $\sigma_{xy} \approx \frac{n_e}{B}$, $n_e$ being the electron density, and $\sigma_{xx} \ll \sigma_{xy}$. Finally, the expression of $R_{xx}$ reads:

$$R_{xx} \propto \left[ \frac{\Delta X^0}{w} - A \sin \left( \frac{2\pi w}{w_c} \right) \right]^2$$

$$\times \left[ 1 + \frac{2X_s}{\sinh(X_s)} e^{-\frac{2\pi}{\hbar c}} \cos \left( \frac{2\pi E_F}{\hbar w_c} \right) \right]$$

With this expression we want to stand out the terms that are going to be responsible of the interference between RIRO’s, first bracket, and the SdHO, second bracket.

Figure 1 exhibits $R_{xx}$ vs the magnetic field $B$ for a) 300 GHz and b) 400 GHz. For both panels we represent on the one hand the total $R_{xx}$ (with RIRO and SdHO all together, black curves online). And on the other hand we represent $R_{xx}$ without SdHO, (red curves online), in order to stand out only the effect of RIRO.

By doing this, we can see intense RIRO in the TH regime that clearly fulfill, for both frequencies two of the key features of RIRO, such as the periodicity in $B^{-1}$ and the 1/4-cycle phase shift of the oscillations minima, $(w/w_c = 5/4, 9/4, 13/4/...).$ Besides, it is interesting to observe with the TH regime, how the radiation induced oscillations overlap with the more rapidly varying with the magnetic field SdHO giving rise to a strong modulation of the latter. This modulation is explained, according to our model, by the interference effect between the harmonic terms showing up in Eq. 4. Thus, this effect is mainly dependent on the radiation frequency and on the Fermi energy or electron density. In physical terms this interference effect comes from the interplay of the average distance advanced by the electron due to scattering, that interferes with the available initial density of states.

In Fig. 2, we present the $P$ dependence of the TH irradiated $R_{xx}$ versus $B$ for increasing $P$, from to 0.1 mW to 6 mW. In Fig. 2a, we exhibit the complete $R_{xx}$ whereas in 2b, we plot $R_{xx}$ without SdHO. In Fig. 2c we plot $\Delta R_{xx}$ that is the difference of irradiated $R_{xx}$ minus the dark one for the labelled peak and valley of 2b, vs $P$. For the latter panel, as expected, we obtain a sublinear dependence of $\Delta R_{xx}$ on $P$. This can be straightforward explained according to our model since the radiation electric field $E_0$ shows up in the numerator of the amplitude of RIRO and, on the other hand, $\sqrt{P} \propto E_0$. Thus, the exponent of the sublinear expression is close to 0.5. But the most interesting effect can be observed in Fig. 2a around $B = 0.6$ T. In this region we obtain the evolution of SdHO as a function of increasing $P$. Interestingly, as in experiments, the SdHO vanish as $R_{xx}$ tends to zero. In other words, we obtain the suppression of SdHO in the region of radiation-induced zero resistance states. According to our model this is because this region corresponds to a situation where the advanced distance $\Delta X \rightarrow 0$, making smaller and smaller the obtained $R_{xx}$, including resistance background and SdHO. Thus, both simultaneously decrease in agreement with the experimental results and assessments.

In Fig. 3 we present calculated results of irradiated $R_{xx}$, $R_{xx}$ without SdHO, $(R_{xx,RIRO})$, and the difference of both, $\delta R_{xx}$, vs $w/w_c$ for three different radiation powers: in panel a) $P = 0.7 mW$, in panel b) $P = 2.7 mW$ and in panel c) $P = 6.0 mW$. The remarkable result is that SdHO turn out to be modulated by the presence of radiation, being the modulation harmonic and periodic in $1/B$ and completely in phase with RIRO. It is also noteworthy that $\delta R_{xx}$ shows an intense interference effect with the appearance of beats with increasing intensity for increasing power (see Figs 3a, 3b and 3c). Some results have been previously obtained in experiments.
The coincidence in phase and period is not trivial and reveals deep physical consequences. Thus, according to our model (Eq. 4), the presence in $R_{xx}$ of the $\Delta X$ term is the main responsible of the effect. The reason is that $\Delta X$ is harmonically dependent on $u/w_e$, getting this dependence across to the the SdHO term. In the end, both contributions end up sharing period and phase as obtained in experiments. In physical terms and as we explain above, the average advanced distance of the scattered electron between radiation-driven LS, strongly modulates the influence of the initial density of Landau states on $R_{xx}$. And this effect can be totally and clearly observed in the TH band and not in the MW due to the coincidence of SdHO and RIRO versus $B$, with TH radiation.

In summary, we have reported on a theoretical work on magnetotransport under terahertz radiation with high mobility two-dimensional electron systems. We have focused on the interaction between the obtained radiation-induced magnetoresistance oscillations and the Shubnikov-de Haas oscillations. We study two effects experimentally obtained with this radiation, first the observed disappearance of the Shubnikov-de Haas oscillations simultaneously with the vanishing resistance on the zero resistance region. And secondly the strong modulation of the Shubnikov-de Haas oscillations at high enough TH radiation power. We have applied the radiation-driven electron orbits model and according to it, both experimental results share the same physical origin: the interference between the average advanced distance due to scattering between driven-Landau states, (radiation-induced resistance oscillations), and the available initial density of Landau states, (Shubnikov-de Haas oscillations).

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