Temperature effects on microwave-induced resistivity oscillations and zero resistance states in 2D electron systems

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In this work we address theoretically a key issue concerning microwave-induced longitudinal resistivity oscillations and zero resistance states, as is temperature. In order to explain the strong temperature dependence of the longitudinal resistivity and the thermally activated transport in 2DEG, we have developed a microscopic model based on the damping suffered by the microwave-driven electronic orbit dynamics by interactions with the lattice ions yielding acoustic phonons. Recent experimental results show a reduction in the amplitude of the longitudinal resistivity oscillations and a breakdown of zero resistance states as the radiation intensity increases. In order to explain it we have included in our model the electron heating due to large microwave intensities and its effect on the longitudinal resistivity.

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Very few experiments in the field of Condensed Matter Physics have produced such intense theoretical and experimental activities in the recent years as the one of longitudinal magnetoresistivity ($\rho_{xx}$) oscillations and zero resistance states (ZRS)\[1,2,3,4\]. These are obtained recently\[5,6,7,8,9,10,11,12\]. Experimental results show a reduction in the amplitude of the longitudinal resistivity oscillations and a breakdown of zero resistance states as the radiation intensity increases. In order to explain it we have included in our model the electron heating due to large microwave intensities and its effect on the longitudinal resistivity.

We obtained the exact solution of the corresponding electronic wave function:

$$\Psi(x,t) = \phi_n(x - X - x_{cl}(t),t) \times \exp \left[ \frac{i}{\hbar} \sum_{m=-\infty}^{\infty} J_m \left( \frac{eE_0}{\hbar} \chi \left( \frac{1}{w} + \frac{w}{\sqrt{(w^2 - w_c^2)^2 + \gamma^4}} \right) \right) e^{int} \right]$$

where $e$ is the electron charge, $\phi_n$ is the solution for the Schrödinger equation of the unforced quantum harmonic oscillator, $w$ the MW frequency, $w_c$ the cyclotron frequency, $E_0$ the intensity for the MW field, $X$ is the center of the orbit for the electron motion, $x_{cl}(t)$ is the classical solution of a forced harmonic oscillator, $x_{cl} = \frac{eE_0}{m^*\sqrt{(w^2 - w_c^2)^2 + \gamma^4}} \cos wt$, $L$ is the Lagrangian and $J_m$ are Bessel functions. According to that model, due to the MW radiation, center position of electronic orbits are not fixed, but they oscillate back and forth harmonically with $w$. The amplitude $A$ for these harmonic oscillations is given by:

$$A = \frac{eE_0}{m^*\sqrt{(w^2 - w_c^2)^2 + \gamma^4}}$$ (2)
Now we introduce the scattering suffered by the electrons due to charged impurities randomly distributed in the sample. Firstly we calculate the electron-charged impurity scattering rate $1/\tau$, and secondly we find the average effective distance advanced when there is no MW response. $\Delta X^{MW} = \Delta X^0 + A \cos \omega t$, 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: $\sigma_{xx} \propto \int dE \Delta X_{MW}^{0}(f_i - f_f)$, being $f_i$ and $f_f$ the corresponding distribution functions for the initial and final Landau states respectively and $E$ energy. To obtain $\rho_{xx}$ we use the relation $\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \approx \frac{\sigma_{xx}}{\sigma_{xx}^2}$, where $\sigma_{xy} \approx \frac{n_{xx}}{B}$ and $\sigma_{xx} \ll \sigma_{xy}$. At this point, we introduce a microscopic model which allows us to obtain $\gamma$ and its dependence on $T_L$, as follows. Following Ando and other authors, we propose the next expression for the electron-acoustic phonons scattering rate valid at low $T_L$:

$$\frac{1}{\tau_{ac}} = \frac{m^* \Xi_{ac} k_B T_L}{\hbar^2 \rho u} < z >$$

where $\Xi_{ac}$ is the acoustic deformation potential, $\rho$ the mass density, $u_i$ the sound velocity and $< z >$ is the effective layer thickness. However $\frac{1}{\tau_{ac}}$ is not yet the final expression for $\gamma$, this will be obtained multiplying $\frac{1}{\tau_{ac}}$ by the number of times that an electron in average can interact effectively with the lattice ions in a complete oscillation of its MW-driven back and forth orbit center motion. If we call $n$ this number, then we reach the final expression: $\gamma = \frac{1}{\tau_{ac}} \times n$. An approximate value of $n$ can be readily obtained in a simple way dividing the length an electron runs in a MW-induced oscillation, ($l_{osc}$), by the lattice parameter of GaAs, $(a_{GaAs})$: $n = \frac{l_{osc}}{a_{GaAs}}$. If $w$ and $w_c$ are approximately of the same order of magnitude, as it is in our case, $l_{osc}$ turns out to be similar to the circular electron orbit length. With the experimental parameters we have at hand and for an average magnetic field it is straightforward to obtain a direct relation between $\gamma$ and $T_L$, resulting in a linear dependence: $\gamma(s^{-1}) \approx 9.9 \times 10^4(s^{-1} K^{-1}) \times T_L (K)$. Now is possible to go further and calculate the variation of $\rho_{xx}$ with $T_L$.

In Fig. 1, we present the calculated $\rho_{xx}$ as a function of $B$, for different $T_L$ at $\nu = w/2\pi = 85\text{GHz}$. In agreement with experiment, as $T_L$ is increased, the $\rho_{xx}$ response decreases to eventually reach the darkness response. In the inset we represent the natural logarithm of $\rho_{xx}$ with the inverse of $T_L$ at the first two deepest minima showing that $\rho_{xx} \propto \exp(-E_{act}/k_B T_L)$, reflecting thermally activated transport. The qualitative behavior of $\rho_{xx}$ as a function of $B$ is very similar to the experimental one, however a quantitative agreement is still lacking. It could be due to the simplified model for the electronic scattering with impurities that we have considered. In both experimental and calculated

**FIG. 1:** (Color on line). Calculated magnetoresistivity $\rho_{xx}$ as a function of $B$, for different $T_L$ at $\nu = 85\text{GHz}$. In the inset we represent $\ln \rho_{xx}$ with $T_L^{-1}$ at the first two deepest minima showing that $\rho_{xx} \propto \exp(-E_{act}/k_B T_L)$ reflecting thermally activated transport.

**FIG. 2:** Schematic diagrams of electronic transport without and with MW corresponding to maxima position. In Fig. 2a no MW field is present: due to scattering, electrons jump between fixed-position orbits and advance an effective average distance $\Delta X^0$. When the MW field is on, the orbits are not fixed but oscillate with $w$. In Fig. 2b, c and d, orbits move backwards during the jump, and on average electrons advance $\Delta X^{MW}$, further than in the no MW case, $\Delta X^0$. As $T_L$ becomes larger the orbits oscillation amplitude $A$ is progressively reduced, reducing at the same time $\Delta X^{MW}$ and giving a progressive reduction in $\rho_{xx}$ maxima.
results, is surprising to see the different behavior of $\rho_{xx}$ maximas and minima as $T_L$ increases. In the first case, $\rho_{xx}$ decreases and in the second one all the opposite, $\rho_{xx}$ increases suggesting $T_L$-activated transport. We can find physical explanation as follows. In Fig. 2, we represent schematic diagrams to explain $T_L$-dependence of maximas: due to the relation between $T_L$ an $\gamma$, an increase in the first one means and increase in $\gamma$ yielding a consequent reduction in the amplitude $A$ (see formula 2) of the MW-driven orbits oscillations. This has a dramatic impact in $\Delta X^{MW}$, which is reduced as $T_L$ is increased. A lesser $\Delta X^{MW}$ (see Figs. 2b, c, and d) will imply a lesser conductivity and a progressive reduction of $\rho_{xx}$ maximas. In Fig. 3 we can observe that, as in the case of maximas, an increase in $T_L$ means a reduction in $A$, but for the $\rho_{xx}$ minima this will produce a progressive larger $\Delta X^{MW}$ and consequently a larger conductivity and $\rho_{xx}$, which means a thermally activated transport. Then quenching of ZRS towards finite resistivity occurs. However if we increase the MW-power, keeping constant $T_L$, $A$ will be progressively larger. We can reach a situation where $A$ is larger than the electronic jump, and the electron movement between orbits cannot take place because the final state is occupied. This situation corresponds to ZRS.

At increasing $T_L$ the darkness response is eventually reached and $\rho_{xx}^{MW}(T_{L}^{\text{highest}}) \rightarrow \rho_{xx}^{\text{dark}}$. In the case of a minimum with ZRS, $\rho_{xx}^{MW}(T_{L}^{\text{lowest}}) \rightarrow 0$. $\Delta T_L$ is the corresponding $T_L$ difference. $\rho_{xx}^{\text{dark}}$ is mainly sample dependent. It implies that $\Delta \rho_{xx}$ and therefore $E_{act}$ will be also sample dependent and with different values for significantly different samples. If we consider the influence of MW-power, it turns out that $\rho_{xx}^{MW}$ is progressively smaller for increasing MW-intensity yielding larger $\Delta \rho_{xx}$ and $E_{act}$ as in experiments. According to our model, the influence of $\Delta T_L$ on $E_{act}$ is coming through $\gamma$ and the consequent damping on the amplitude $A$. The mechanism of electron scattering responsible for the damping will be very important in the value of $E_{act}$. Thus, if the interaction is strong, the damping will be intense and $A$ will be reduced very fast. Therefore $\Delta T_L$ and $E_{act}$ will be small. However, if the interaction is weak, all the opposite will occur. We propose the electron-acoustic phonon interaction as the candidate to be responsible for the damping, reproducing most experimental features: linear behavior for $\ln \rho_{xx}$ vs $1/T_L$, value of $\Delta T_L$ and the order of magnitude of $E_{act}$.

Recent experiments show that at sufficiently high MW intensities the $\rho_{xx}$ oscillatory amplitude instead of getting larger, becomes reduced by further in-
creases in the MW intensity. A breakdown of ZRS is also observed. We propose that it can be produced by electron heating occurring as the field intensity increases. To show that, we analyze theoretically the dependence of $\rho_{xx}$ on $T_e$. It is clear that one of the effects of a progressive increase in the MW power will be electron heating and the corresponding increase in $T_e$. This will be reflected directly in the electronic distribution functions, $f_i$ and $f_f$, with the corresponding smoothing effect. Eventually we will obtain a progressive reduction in $(f_i - f_f)$ and therefore in $\rho_{xx}$. We find a situation where a MW power further increase yields two opposite effects on $\rho_{xx}$ maxima. On the one hand a power rise will increase $A$ (see formula 2) which, in the maxima position, corresponds to larger $\Delta X^{MW}$ giving a $\rho_{xx}$ rise. This is what is found in experimental and calculated results when the MW intensity is modest (see Fig. 4a). On the other hand, a MW power rise yields also electron heating, increasing $T_e$ ($E_0^2 \propto T_e^3$ according to available experimental evidence[16]) which, as we said above, will reduce the difference $(f_i - f_f)$ giving a reduction in $\rho_{xx}$ maxima. This is what we find when the increasing MW power reaches a certain threshold value where the second effect is stronger than the first one, resulting in a progressive reduction of $\rho_{xx}$ maxima (see Fig. 4b). In Fig.4b (see inset) we reproduce another surprising experimental result[13, 14] as is the breakdown of ZRS states at high excitation power. Here at the minima, breakdown is characterized by a $\rho_{xx}$ positive structure. Following our model, if we rise the MW intensity, we will eventually reach the situation where the orbits are moving forward but their amplitude is larger than the electronic jump, therefore $\Delta X^{MW} < 0$. In that case the jump is blocked by Pauli exclusion principle, $(f_i - f_f) = 0$, $\rho_{xx} = 0$ and we reach the ZRS regime. However at high MW-intensities, in the ZRS regime, the MW-induced amplitude $A$ is larger than the electronic jump and therefore the final state results to be below the Fermi energy. Under this regime, being $T_e > 0$ and due to the smoothing effect in the distribution function, we reach a situation where $f_f < 1$, $f_i < 1$ and $(f_i < f_f)$. Eventually we obtain that $(f_i - f_f)$ can be negative. In this situation $\Delta X^{MW} < 0$ and $(f_i - f_f) < 0$, will produce an effective positive net current and positive $\rho_{xx}$ in the middle of the ZRS region, resulting in the breakdown of this effect.

In summary, we have presented a theoretical model on the different effects of $T$ on $\rho_{xx}$ MW-driven oscillations and ZRS. The strong $T_L$-dependence on $\rho_{xx}$ and $T_L$-activated transport in 2DEG are explained through a microscopic model based on a damping process of the MW-driven orbits dynamics by interaction with acoustic phonons. Recent experimental results regarding a reduction in the amplitude of $\rho_{xx}$ oscillations and breakdown of ZRS due to a further rise in the MW power are explained in terms of electron heating.

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