Microwave radiation induced magneto-oscillations in the longitudinal and transverse resistance of a two dimensional electron gas

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We confirm the existence of magneto-resistance oscillations in a microwave-irradiated two-dimensional electron gas, first reported in a series of papers by Zhudov et al.[1] and Mani et al.[2]. In our experiments, on a sample with a more moderate mobility, the microwave induced oscillations are observed not only in the longitudinal - but also in the transverse-resistance (Hall resistance). The phase of the oscillations is such that the decrease (increase) in the longitudinal resistance is accompanied by an increase (decrease) in the absolute value of the Hall resistance. We believe that these new results provide valuable new information to better understand the origin of this interesting phenomenon.

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A. Introduction

The new physics that results from subjecting a high mobility two-dimensional electron gas (2DEG) to magnetic fields continues to provide new and fascinating phenomena. Among them is the recently reported observation of oscillations in the longitudinal magneto-resistance ($\rho_{xx}$) of a 2DEG irradiated by microwaves with frequencies in the range 5 - 100 GHz[1]. These oscillations have been observed in samples with very high mobility, at moderately low temperatures $T \sim 1K$, and at low magnetic fields ($\hbar \omega \sim \hbar \omega_c$). The periodicity of these oscillations is determined by the ratio of $\hbar \omega / \hbar \omega_c$, in contrast to the well established case of Shubnikow-de Haas (SdH) oscillations which they are determined by the ratio $E_F / \hbar \omega_c$. Here, as usual: $\hbar \omega_c = \hbar e B / m^*$ is the electron cyclotron energy, with $m^*$ the electron effective mass and $E_F$ denotes the Fermi energy. Under strong microwave irradiation and with samples that have a sufficiently high mobility, the minima in $\rho_{xx}$ become transformed into "zero resistance states "[2].

It has been proposed[3,4,5] that these microwave induced resistance oscillations (MIROs) can be understood in terms of an additional, microwave-induced current which flows with or against the direction of the applied electric field, depending on whether $n - 1/2 \lesssim \omega / \omega_c < n$ or $n < \omega / \omega_c \lesssim n + 1/2$, with $n = 1, 2, 3, \ldots$ integers. It has further been suggested that zero resistance states appear because of domain formation when the absolute conductivity becomes negative[3]. Alternatively, this effect may reflect even more elaborate physics[2]. A characteristic of the theoretical treatments is that no microwave induced changes to $\rho_{xx}$ are expected for $\omega / \omega_c$ exactly equal to 1,2,3,...[3,4,5]. Conventional cyclotron resonance absorption, which involves direct excitations and conservation of the motion of the electron cyclotron orbit, does not result in any additional current (i.e. does not change the conductivity). The additional current appears as a result of indirect (off-diagonal) electron excitations and involves other factors, such as impurities or phonons[3,4,5]. Therefore MIROs are not necessarily triggered by a resonant absorption process, but more likely result from non-resonant microwave-induced excitations of the 2DEG, with the modulation of $\rho_{xx}$ being a consequence of periodically conditions for the additional current to flow preferentially with or against the applied electric field.

Diagrammatic calculations of the changes in the conductivity tensor induced by the microwave-excited disorder-scattered electrons reproduce the main experimental trends, in particular the observed period and the phase[4]. Nevertheless, other experimental features such as the exact shape of the oscillations as a function of magnetic field[7] and the temperature dependence of the MIROs amplitudes are not as well understood. Another puzzle is that while the theory[4] invokes an impurity-disorder mechanism to explain the MIROs, it is found experimentally that the oscillations become more clearly pronounced as the mobility is increased and the disorder is reduced.

In this paper we address another relevant issue, whether MIROs are a unique property of the longitudinal resistance (or alternatively $\sigma_{xx}$) or whether they also appear in the transverse resistance $\rho_{xy}$. So far, MIROs have been reported exclusively in measurements of $\rho_{xx}$ or $\sigma_{xx}$[5]. It is sometimes argued that the absence of microwave induced features in $\rho_{xy}$ implies that MIROs have a classical origin rather than being a many-body effect. Theoretically, it has been predicted that both $\rho_{xx}$ and $\rho_{xy}$ should be influenced by microwave irradiation and that the resistance changes $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$, at least under some approximations, should be comparable in magnitude[4]. Results are presented here that show, for the first time, that microwave induced changes, of a similar magnitude, can be observed in measurements of both $\rho_{xx}$ and $\rho_{xy}$. It is shown that the observed oscillations in $\rho_{xy}$
cannot be attributed to more trivial effects, such as an admixture of $\rho_{xx}$ and $\rho_{xx}$ but rather must be associated with microwave induced oscillations in both the longitudinal conductivity $\sigma_{xx}$ and the transverse conductivity $\sigma_{xy}$. Possible consequences of our experimental findings are discussed.

### B. Experimental

The measurements have been performed at He$^4$ bath temperatures ($T = 1.4 - 4.2K$), on a GaAs/AlGaAs heterojunction (grown at NRC) that had a 2DEG mobility of $\mu = 4.0 \times 10^6cm^2/Vs$ and density of $n = 1.9 \times 10^{13}cm^{-2}$ after a brief illumination using a red LED. The sample was cleaved into a rectangular shape to form a 8x2 mm$^2$ Hall bar and contacted at the edges using small In dots. The length-to-width ratio between potential and Hall contacts was 1.3/2.

An Anritsu 69377B Signal Generator (operating at 0.01-50 GHz, with typical output power of a few mW) was used as the source of microwaves(MWs). They were delivered into the cryostat through a semirigid 0.085 inch coaxial cable which had a typical attenuation factor of 6-10dB near 50GHz. The cable was terminated with a zero resistance state), and MIROs [1, 2] (although the mobility of the sample used was too low to achieve “zero resistance” states), and confirms again that phenomena is universal, independent of the source of the sample. Each $\Delta \rho_{xx}$ trace is plotted against the dimensionless parameter $\omega/\omega_c$, i.e., the ratio of microwave to cyclotron frequency, assuming the cyclotron mass, $m^* = 0.067m_e$. In agreement with previous observations [1, 2], $\Delta \rho_{xx}$ is found to be an oscillatory function of the inverse magnetic field, with the fundamental period $\Delta(1/B) = (1/B)(\omega_c/\omega)$. It is apparent from Fig. 1 that the oscillations are damped by increasing temperature and by decreasing magnetic field, microwave power or microwave frequency. The dependence of $\Delta \rho_{xx}$ on the magnetic field can be roughly described as

$$\Delta \rho_{xx} = -A \exp(-D_M/\hbar \omega_c) \sin(2\pi \omega/\omega_c)$$

with a phase corresponding to a positive coefficient A. The damping parameter $D_M$ is relatively insensitive to microwave power or frequency. We find that $D_M \approx 0.3meV$ at $T = 1.64K$ and increases somewhat at higher temperatures. While Eq.(1) provides a good description of the higher order oscillations there are deviations around the fundamental cyclotron resonance (n=1); the exact positions of the maxima and minima in $\Delta \rho_{xx}$ become sensitive to the experimental parameters such as microwave power and temperature. This may be associated with the effect of the cyclotron resonance which can produce significant changes in the dielectric function of the 2DEG. The most robust and well defined feature of the MIROs are the positions of the zeros in $\Delta \rho_{xx}$ that occur when $\omega/\omega_c = 1, 2, 3, ...$. This is in agreement with theoretical predictions [1, 2, 3, 4].

The standard expression for the amplitude of the SdH

![Fig. 1](image-url)
oscillations is $\Delta \rho_{xx} = 4\rho_0 D_{th}(X_T) \exp(-\pi/\omega_c\tau_q)$  

(2)

where the thermal damping factor, $D_{th}$, is given by $X_T/\sinh(X_T)$ with $X_T = 2\pi^2 kT/\hbar\omega_c$ and where $\tau_q$ is the quantum lifetime.

If the SdH oscillations in $\rho_{xx}$ (see for example figure 2) are analysed using this expression the damping is dominated by $D_{th}$ and no oscillations are visible in the low field region when the MIROs appear. However, measurements at lower temperatures (below 100 mK) in another sample cut from the same wafer, show SdH oscillations to below 0.05 T which can be used to extract a value for $\tau_q$ of approximately 10 ps. This corresponds to a damping coefficient $\pi\hbar/\tau_q$ of 0.27 meV, essentially identical to the coefficient $D_M$ obtained above for the MIROs.

At 0.1 tesla, $\tau_q = 10$ ps corresponds to a (Gaussian) Landau level broadening parameter of order 0.04 meV compared with the cyclotron spacing of 0.17 meV. Therefore, despite the fact that thermal blurring of the distribution function suppresses the $\Delta \rho_{xx}$ oscillations, at higher fields a well defined Landau level structure persists in the very low fields corresponding to $\omega_c/\omega \lesssim 1$.

For conventional SdH oscillations convolution of the Fermi function with the density of states produces a strong thermal degradation of the oscillations but this appears not to be the case for MIRO’s. One explanation for this might be that the normal role of the Fermi function in producing a thermal smearing is masked by a stronger perturbation of the distribution function induced by the microwave radiation. It is only at higher temperatures (above about 1.5K) that the Fermi function can cause additional thermal smearing and give rise to a temperature dependent $D_M$.

In the following section we show that MIROs are not only evident in the longitudinal resistance but can be also observed in the Hall (transverse) resistance $\rho_{xy}$. This can be seen in Fig. 2, which illustrates the result of simultaneous measurements of $\rho_{xx}$ and $\rho_{xy}$ (right scale) and the MW induced deviations $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$ (left axis). Despite the noise in the $\Delta \rho_{xy}$ trace it is clear that microwaves affect both resistances, and that the amplitudes of the two sets of oscillations are very similar. The noise is relatively large because the high mobility of the sample means $\Delta \rho_{xy}/\rho_{xy}$ is of order 100 times smaller than $\Delta \rho_{xx}/\rho_{xx}$ when MIROs are observed so the inevitable errors associated with taking differences between large numbers become much more important for $\Delta \rho_{xy}$.

Note that $\Delta \rho_{xy}$, like $\rho_{xy}$, changes sign in reversed magnetic fields. This means the observation of MIROs in $\rho_{xy}$ cannot be attributed to a trivial admixture of $\rho_{xx}$ into the $\rho_{xy}$ signal, due for example to misaligned contacts.

The absolute sign of $\Delta \rho_{xy}$ depends on a sign convention but the fact that the sign of $\Delta \rho_{xy}/\rho_{xy}$ is the opposite to the sign of $\Delta \rho_{xx}$ is an unambiguous experimental observation that can be tested against theory.

Simple quantitative arguments can also be made to confirm that $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$ do not just reflect changes in $\sigma_{xx}$ exclusively. If the standard expressions are used for inverting the conductivities (viz. $\rho_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{xy}^2)$) and $\rho_{xy} = \sigma_{xy}/(\sigma_{xx}^2 + \sigma_{xy}^2)$) then it is straightforward to show that a small change in $\Delta \sigma_{xx}$ will produce changes in $\rho_{xx}$ and $\rho_{xy}$ related by $\Delta \rho_{xy} = -\frac{2K}{1-K} \Delta \rho_{xx}$ where $K = \rho_{xx}/\rho_{xy}$. While this gives the correct (observed) phase relationship between the two terms K is typically 0.02 so under the actual experimental conditions $\Delta \rho_{xy}$ is predicted 20 times smaller than $\Delta \rho_{xx}$, in sharp contrast to the experimental results which show the ratio is actually about 2. An equivalent calculation shows, likewise, that the observed oscillations in $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$ cannot result from changes in $\sigma_{xy}$ alone. We therefore conclude that both $\sigma_{xx}$ and $\sigma_{xy}$ are independently influenced by microwaves. The results in Fig 2 showing $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$ oscillating in anti-phase correspond, for example, to an increase (decrease) in effective electron concentration when the longitudinal conductivity $\sigma_{xx}$ increases (decreases). A theoretical determination of the phase relationship between $\Delta \rho_{xx}$ and $\Delta \rho_{xy}$ has not yet been addressed directly.

FIG. 2: Magnetic field dependencies of (a) the transverse magnetoresistivity $\rho_{xy}$ and (b) the longitudinal magnetoresistivity $\rho_{xx}$ and their deviations from dark values induced by microwave radiation $f=49.8$ GHz at $T=1.7$ K.
D. Conclusions

In conclusion, we have confirmed the observation of microwave induced magneto-oscillations (MIROs) in the longitudinal resistance of a 2DEG with a periodicity defined by the ratio of microwave to cyclotron frequencies [1, 2].

Our results indicate that a necessary condition for the observation of these oscillations is a pronounced modulation of the electronic density of states (Landau levels), in general agreement with predictions of existing theoretical models [3, 4, 5].

The temperature dependent damping of MIROs is very different from the thermal damping of the Shubnikov-de Haas oscillations. It is not clear whether this is related to a temperature dependence of the Landau level broadening or some other mechanism. Experiments to address this issue are in progress.

If MIROs are due to the scattering by impurities of microwave-excited electrons but at the same time require a pronounced modulation in the density of states, a subtle criteria would exist for optimum sample quality. It would be interesting to check this if even higher mobility samples become available. However, phonon-assisted processes may also play a role [7] and effects resulting from the interplay between one-particle and collective excitations in the 2DEG [10] should also not be neglected. More experiments, and in particular complementary microwave absorption measurements, are needed to achieve a better understanding of this fascinating phenomena.

The major new result reported here is that MIROs are not only present in the longitudinal resistance but can also be observed in the transverse component of the magneto-resistance. This is a non-trivial effect and requires that \(\sigma_{xx}\) and \(\sigma_{xy}\) both oscillate independently. The relative phase of the \(\Delta \rho_{xx}\) and \(\Delta \rho_{xy}\) oscillations experiment remains to be compared to theoretical predictions.

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