Shubnikov–de Haas oscillations in a two-dimensional electron gas under subterahertz radiation

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We report on magnetotransport measurements in a two-dimensional (2D) electron gas subject to subterahertz radiation in the regime where Shubnikov–de Haas oscillations (SdHOs) and microwave-induced resistance oscillations (MIROs) coexist over a wide magnetic field range, spanning several harmonics of the cyclotron resonance. Surprisingly, we find that the SdHO amplitude is modified by the radiation in a nontrivial way, owing to the oscillatory correction which has the same period and phase as MIROs. This finding challenges our current understanding of microwave photoresistance in 2D electron gas, calling for future investigations.

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When a two-dimensional electron gas (2DEG) is subject to a perpendicular magnetic field $B$ and low temperature $T$, the longitudinal resistivity $\rho$ exhibits Shubnikov–de Haas oscillations (SdHOs), owing to a quantum correction

$$\delta \rho_{\text{SdH}} = -S \cos \pi \nu, \quad S = 4 \rho_0 \lambda D_T. \quad (1)$$

Here, $\nu$ is the filling factor, $\rho_0$ is the resistivity at $B = 0$, $\lambda = \exp(-\pi/\omega_c \tau_q)$ is the Dingle factor, $\tau_q$ is the quantum lifetime, $D_T = \lambda' \tau_q / \sin \lambda' \tau_q$, $\lambda' = 2\pi^2 k_B T / \hbar \omega_c$, $\omega_c = eB/m^*$ is the cyclotron frequency, and $m^*$ is the effective mass. When a 2DEG is subject to radiation of frequency $\omega = 2\pi f$, $\rho$ also reveals microwave-induced resistance oscillations (MIROs) [1–11] which, according to Refs. [12,13], are given by

$$\delta \rho_{\text{MIRO}} = -2\pi \epsilon \rho_0 \mathcal{P} \eta \lambda^2 \sin 2\pi \epsilon. \quad (2)$$

where $\epsilon = \omega/\omega_c$, $\mathcal{P}$ is the dimensionless radiation intensity [13–17], $\eta = \tau / 2\tau_r + 2\tau_r / \tau$, $\tau$ is the transport lifetime, $\tau_r$ is the inelastic lifetime, and $\tau_r^{-1} = 3\tau_0^{-1} - 4\tau_1^{-1} + \tau_2^{-1}$ [18]. When the photoresistance $\delta \rho_{\text{MIRO}}$ approaches the dark resistivity $\rho_0$ by absolute value, the MIRO minima evolve into zero-resistance states [19–27], which are understood in terms of current domains [28–31].

The majority of MIRO studies have been performed at relatively high $T$ and low $f$, at which SdHOs are strongly suppressed. Extending experiments to higher $f$ [23,32–39] and lower $T$ yields a regime where SdHOs and MIROs coexist, allowing one to explore possible mixing between these two types of quantum oscillations and to investigate the effect of radiation on SdHOs in general.

It has been known for some time that microwaves suppress SdHOs in the vicinity of cyclotron resonance, $\epsilon \approx 1$ [32,33,35]. As SdHOs are sensitive to the thermal smearing of the Fermi surface, this suppression can be directly linked to absorption, which is indeed the strongest near the cyclotron resonance [40–42]. Away from the cyclotron resonance, our understanding of how microwaves affect SdHOs is definitely lacking. Some experiments have shown that the effect of microwaves on the SdHO is the weakest near half integer $\epsilon$, which was attributed to the suppression of both inter- and intra-Landau level absorption [34,35]. Another experiment [37] found that as the MIRO minima approach zero, the SdHO amplitude vanishes in proportion with the background resistance. Reference [37] then argued that in an irradiated 2DEG, $\rho_0$ in Eq. (1) should be replaced by $\rho_{\text{MIRO}} \approx \rho_0 + \delta \rho_{\text{MIRO}}$.

There exist several mechanisms that could lead to the modification of the SdHO by radiation. First, the absorption coefficient $A$ is expected to acquire an oscillatory quantum correction $[6,40,43–46]$ which, according to Refs. [40,46], is given by

$$\delta A_q \approx 2A_D \lambda^2 \cos 2\pi \epsilon, \quad (3)$$

where $A_D$ is a classical absorption described by a Drude formula $[16,46,47]$. Since oscillations in $A$ translate to oscillations in $T$ [41,42], Eq. (3) suggests that the microwave-induced suppression of SdHO is maximized near the cyclotron resonance and, to a much lesser extent, near its harmonics,

$$\epsilon = n = 1, 2, 3, \ldots. \quad (4)$$

In addition, theory also predicts a radiation-induced oscillatory correction, of the order $O(\lambda)$ [48], to the dc resistivity. While the inelastic mechanism produces no such contribution [49], the displacement mechanism dictates that $S$ in Eq. (1) acquires an oscillatory correction and should be replaced by $[49,50]$

$$S_\omega = S \left[ 1 - \mathcal{P} \frac{\tau}{\tau_r} \sin^2(\pi \epsilon) \right], \quad (5)$$

suggesting that the SdHO amplitude is minimized at

$$\epsilon = n + 1/2 = 3/2, 5/2, 7/2, \ldots. \quad (6)$$

a condition orthogonal to Eq. (4). Finally, the same condition, Eq. (6), can be expected from classical oscillations in magnetoresistance [51], $\delta A_q / A_D \sim - \cos 2\pi \epsilon$, which can be stronger than quantum oscillations, given by Eq. (3), in a typical 2DEG.
In this Rapid Communication we experimentally investigate the photoresistance in high-quality 2DEGs. Using high \( f \), low \( \mathcal{P} \), and low \( T \) allows us to overlap MIROs and SdHOs over a wide range of \( \epsilon \) and to investigate the SdHO wave form near multiple harmonics of the cyclotron resonance. Our data reveal pronounced modulation of the SdHO amplitude which persists to \( \epsilon \approx 6 \). Surprisingly, even though the modulation is periodic in \( \epsilon \), it cannot be described by either Eqs. (3) and (4) or Eqs. (5) and (6). Instead, the radiation-modified SdHO amplitude closely replicates the MIRO wave form [see Eq. (2)], suggesting a nontrivial mixing of MIROs and SdHOS. While it is well established that quantum oscillations of the order \( O(\lambda^2) \) interfere with each other [14,15,52–58], the observed correlation between MIRO \( \sim O(\lambda^2) \) and SdHO \( \sim O(\lambda) \) is totally unexpected [59].

While we have obtained similar findings from a variety of samples grown at Princeton and Purdue, in what follows we present the results from two Purdue-grown Hall bars, I and II, samples grown at Princeton and Purdue. In addition, one can now clearly see that, in contrast to the “dark” amplitude \( \delta \rho_{SdH} \), MIRO hints at the strong correlation between the two quantities.

In Fig. 1 we present the magnetoresistivity \( \rho_{\omega}(B) \) measured in sample I (II) irradiated by microwaves of \( f = 378 \) (290) GHz at \( T = 0.3 \) K. The vertical lines are drawn at the cyclotron resonance harmonics, \( \epsilon = \omega/\omega_c \approx 2.3, 4, \ldots \). Both panels also show \( \rho_{MIRO}(B) \) (light curves) obtained by averaging out SdHOS [see Eq. (8)].

Eq. (8). Since \( \rho_{MIRO} \) oscillate much slower than SdHOS [cf. Eq. (7)], it can be easily obtained by averaging out faster SdHOS. Obtained in this way, \( \rho_{MIRO}(B) \) is shown in both panels of Fig. 1 by light curves running midway between the SdHO maxima and minima.

Having found \( \rho_{MIRO} \), we now use Eq. (8) to obtain \( \delta \rho_{SdH} \) by subtracting \( \rho_{MIRO} \) from \( \rho_{\omega} \), both shown in Fig. 1. The results for samples I and II are presented as a function of \( \epsilon \) in Figs. 2(a) and 2(b), respectively. For comparison, we also include \( \rho_{\omega} \) and \( \delta \rho_{SdH} \), as marked. The latter was found using Eq. (7) by subtracting the smooth part of the resistivity \( \rho_{sm} \) from \( \rho(B) \) measured without irradiation. Direct examination of the SdHO reveals that \( \delta \rho_{SdH} \), which monotonically decays with \( \epsilon \) in accordance with Eq. (1), \( \delta \rho_{SdH} \) exhibits clear signs of modulation with the period close to unity. Furthermore, a comparison of \( \delta \rho_{SdH} \) and \( \rho_{MIRO} \) hints at the strong correlation between the two quantities.

We next extract the amplitude of \( \delta \rho_{SdH} \), shown in Fig. 2, and examine it in more detail. In Fig. 3 we present the extracted amplitude \( S_\omega \) (open circles) and \( \rho_{MIRO} \) (solid circles) as a function of \( \epsilon \) on a log-linear scale. Once plotted together, the
correlation between $S_\omega$ and $\rho_{\text{MIRO}}$ becomes very clear—both quantities oscillate in phase with each other. In other words, radiation induces minima in the SdHO amplitude at

$$\epsilon \approx n + 1/4 = 5/4, 9/4, 13/4, \ldots, \quad (9)$$

in contrast to both the scenario considering oscillations in magnetoabsorption [Eq. (3)] and the one predicting direct modification of the SdHO [Eq. (5)].

In the remaining part of this Rapid Communication we search for an empirical relation describing the SdHO amplitude in the presence of radiation. To this end, we extract and compare the oscillatory parts in $S_\omega$ and in $\rho_{\text{MIRO}}$. More specifically, we introduce the dimensionless quantity

$$\delta S_\omega / S = S_\omega / S - 1,$$

where $S$ is the smooth, nonoscillating part of the SdHO amplitude shown in Fig. 3 by straight lines, and present the results in Fig. 4. For comparison, we also plot the oscillatory part of MIRO, $\delta \rho_{\text{MIRO}} / (2\pi \epsilon \lambda^2 \rho_0)$.

We immediately see that both quantities oscillate around zero without noticeable decay, confirming that exponential factors have been properly eliminated. As already anticipated, a very good agreement in both the period and the phase is found almost everywhere, except at $\epsilon \lesssim 2$ in sample II. The latter can be linked to increased absorption close to the cyclotron resonance, where SdHOs are suppressed due to resonant heating [32,33,35,62]. The absence of such a deviation in sample I can be attributed to considerably higher $f$, which reduces the influence of the cyclotron absorption peak. Interestingly, combining Eq. (11) with Eq. (2), one finds that $\alpha \approx P \eta$.

Finally, we examine the proposal of Ref. [37] that the SdHO under irradiation can be described by Eq. (1) with $\rho_0$ replaced by $\rho_0 + \delta \rho_{\text{MIRO}}$ [63]. Taking this approach, one obtains $\delta S_\omega / S = \delta \rho_{\text{MIRO}} / \rho_0$, a result similar to Eq. (11), but with an extra factor $2\pi \epsilon \lambda^2$, which has significant dependence on $\epsilon$. Indeed, as $\epsilon$ increases from 2 to 6, $2\pi \epsilon \lambda^2$ decreases by nearly a factor of 5 for sample I. In contrast, our data shown

the SdHO amplitude is given by

$$S_\omega \approx S(1 - \alpha \sin 2\pi \epsilon), \quad (10)$$

where $\alpha$ is a dimensionless $\epsilon$-independent constant, showing that $\delta S_\omega$ is a correction of order $O(\lambda)$, just as the SdHOs themselves.

The most surprising finding, however, is a quantitative correlation between $\delta S_\omega$ and $\delta \rho_{\text{MIRO}}$, namely,

$$\frac{\delta S_\omega}{S} \approx \frac{\delta \rho_{\text{MIRO}}}{2\pi \epsilon \lambda^2 \rho_0} \approx -\alpha \sin 2\pi \epsilon, \quad (11)$$

where all parameters have been obtained experimentally. The observed correlation is completely unexpected and is found almost everywhere, except at $\epsilon \leq 2$ in sample II. The latter can be linked to increased absorption close to the cyclotron resonance, where SdHOs are suppressed due to resonant heating [32,33,35,62]. The absence of such a deviation in sample I can be attributed to considerably higher $f$, which reduces the influence of the cyclotron absorption peak. Interestingly, combining Eq. (11) with Eq. (2), one finds that $\alpha \approx P \eta$.

Finally, we examine the proposal of Ref. [37] that the SdHO under irradiation can be described by Eq. (1) with $\rho_0$ replaced by $\rho_0 + \delta \rho_{\text{MIRO}}$ [63]. Taking this approach, one obtains $\delta S_\omega / S = \delta \rho_{\text{MIRO}} / \rho_0$, a result similar to Eq. (11), but with an extra factor $2\pi \epsilon \lambda^2$, which has significant dependence on $\epsilon$. Indeed, as $\epsilon$ increases from 2 to 6, $2\pi \epsilon \lambda^2$ decreases by nearly a factor of 5 for sample I. In contrast, our data shown
in Fig. 4(a) show virtually no decay at $\epsilon \gtrsim 2$. In addition, if this factor were actually present, the correction to SdHO would have been up to $>3$ ($>5$) times larger than observed in sample I (sample II). We thus conclude that the proposal of Ref. [37] is irrelevant to our findings.

In summary, we have studied the photoresistance in high-quality 2DEG subject to low temperatures and high microwave frequencies, which allowed us to overlap MIRO and SdHO over multiple harmonics of the cyclotron resonance. Our data revealed pronounced modulation of the SdHO which is periodic in $\epsilon$, with the period equal to unity, and the phase matching that of the MIRO. This result does not fit existing theories considering either magnetoabsorption or photoresistance. Most remarkably, we have found that once the exponential factors are eliminated, the oscillatory part of the SdHO amplitude matches that of MIRO quantitatively, without any adjustable parameters. This finding allowed us to deduce an empirical relation for the SdHO amplitude in irradiated 2DEG, given by Eqs. (10) and (11). Taken together, our study reveals that the current understanding of SdHos in irradiated 2DEG is lacking, calling for further investigations.

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FIG. 4. (Color online) (a) [$b$] $\delta S_\omega /S$ (open circles) and $\delta \rho_{\text{MIRO}}/(2\pi^2 \epsilon^2 \rho_0)$ (solid circles), extracted from the data in Fig. 1(a) [Fig. 1(b)], as a function of $\epsilon$.

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[59] Under conditions of our experiment, in sample I (II) we estimate $\tau_q$ to be 2 (3) ps from SdHOs and 4.4 (8.2) ps from MIROs. However, the accurate determination of SdHO $\tau_q$ requires extremely slow sweeps at very low $B$, which were not attempted because the exact knowledge of $\tau_q$ is not crucial for our study.
[60] $\rho_{sm}$ is not significantly different from $\rho_\rho$, except in 2DEG exhibiting strong negative magnetoresistance [64–67].
[61] Strictly speaking, $\rho_{sm} \neq \rho_{sm}$ because of radiation-induced heating and $T$ dependence of $\rho_{sm}$.
[62] While all samples surveyed have shown a correlation between MIROs and SdHOs, in many of them MIROs rapidly decayed with increasing $f$. A result, modulation of the SdHOs was observed only up to $f \approx 2$, where the excess heating due to the proximity to the cyclotron resonance precluded a quantitative analysis of the wave forms.
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