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Radiation-induced oscillatory magnetoresistance in a tilted magnetic field in $GaAs/Al_xGa_{1-x}As$ devices

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We examine the microwave-photoexcited magnetoresistance oscillations in a tilted magnetic field in the high-mobility two-dimensional electron system (2DES). In analogy to the 2D Shubnikov–de Haas effect, the characteristic field B_f and the period of the radiation-induced magnetoresistance oscillations appear dependent upon the component of the applied magnetic field that is perpendicular to the plane of the 2DES. In addition, we find that a parallel component $B_{\parallel}$ in the range of $0.6 < B_{\parallel} < 1.2$ T at a tilt angle of $\theta = 80°$ leaves the oscillatory pattern essentially unchanged.

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I. INTRODUCTION

The possibility of inducing unusual zero-resistance states and magnetoresistance oscillations by photoexciting a high-mobility $GaAs/Al_xGa_{1-x}As$ device, with radiation from the microwave and terahertz parts of the electromagnetic wave spectrum,[1–6] has recently motivated a broad theoretical examination of the photoexcited steady states of the low-dimensional electron system.[7–18]

At present, the observed radiation-induced resistance oscillations are generally attributed to a field-dependent scattering at impurities and/or a steady-state change in the electronic distribution function, as a result of photoexcitation.[7,9,11–15] It turns out that in both of these theoretical scenarios, the amplitude of the magnetoresistance oscillations can increase with the radiation intensity, in analogy to the experimental observations. Consequently, the calculated resistivity or conductivity can be made to take on negative values at the minima of the oscillatory magnetoresistivity (or magnetoconductivity) for sufficiently large radiation intensities.[7,9,11,12,14,15] A path for realizing zero-resistance states from the theoretically indicated negative resistivity or conductivity under photoexcitation has been provided by Andreev *et al.*,[10] who suggested that a physical instability of the negative resistivity or conductivity state should transform it into a zero-resistance state, through the development of dissipationless current domains. In this approach, the current domains reconfigure themselves to accommodate changes in the applied current.[10]

Recently, an alternate scenario has been provided by Inarrea and Platero,[17] who suggest that a blocking of the final states for scattering, due to an exclusion principle, leads to the zero-resistance states observed in experiment. Although there exist other models, the above-mentioned theories seem to constitute the popular approaches for understanding the observed phenomena.

Transport studies in a tilted magnetic field have been utilized in the past to establish the effective system dimensionality in electronic transport. In quasi-two-dimensional electronic systems (2DESs), they have also served to separate the relative contributions of spin and orbital effects. For example, it is known that in an applied magnetic field B, when the 2DES specimen is tilted at an angle θ, the period of Landau-quantization-dependent (orbital) effects, such as the Shubnikov–de Haas (SdH) effect, is determined by the sample-perpendicular magnetic field component $B_{\perp}$. On the other hand, it is also known that spin-related phenomena typically depend upon B instead of $B_{\perp}$ since the spin degree of freedom couples to the total applied magnetic field.[19]

We examine here the radiation-induced oscillatory resistance in a tilted magnetic field to experimentally confirm the effective dimensionality, and examine the relative influence of the perpendicular and in-plane ($B_{\parallel}$) components of the applied magnetic field.[1] This extended report seems timely in light of the recent observation of the anomalous disappearance of radiation-induced zero-resistance states and associated magnetoresistance oscillations under the application of a small ($B_{\parallel} \approx 0.5$ T) parallel magnetic field on the 2D electron system.[20] A summary of our tilt field studies appeared in Ref. 1.

Briefly, we find that the characteristic field scale B_f, or equivalently the periodicity (B_f^{-1}), of the observed oscillations is determined by $B_{\perp}$, analogous to the characteristics of the 2D Shubnikov–de Haas effect.[21] In addition, the applied $B_{\parallel}$ seems not to quench the observed phenomena to a tilt angle $\theta = 80°$, although the radiation-induced magnetoresistance oscillations and associated zero-resistance states do disappear in the $\theta \rightarrow 90°$ limit.

II. EXPERIMENT

For these experiments, specimens characterized by $n \approx 3 \times 10^{11}$ cm^{-2} and $\mu \leqslant 1.5 \times 10^7$ cm^2/V s were mounted within a microwave waveguide, and immersed in liquid helium in a low-temperature cryostat, within the bore of a superconducting solenoid.[1] *In situ* sample rotation was carried out by fixing the sample on a geared rotatable platform, which could be turned with the aid of a geared shaft that extended outside the cryostat. The quoted tilt angles θ are the mechanically set values, which could be incremented in units of 10°. The gear backlash and/or play produces an uncertainty in the orientation of up to ±2°. Thus, the actual tilt angle can differ slightly from the preset value. This differ-

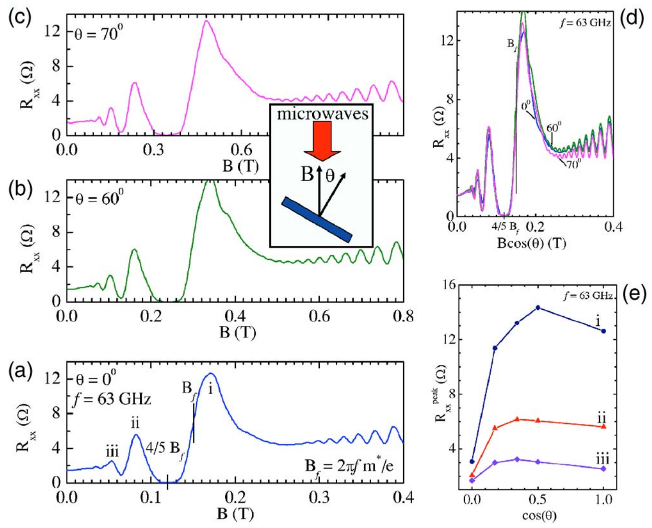

FIG. 1. (Color online) This figure illustrates the effect of tilting the microwave-excited two-dimensional electron system with respect to the magnetic field and the direction of microwave propagation. The tilt angle θ=(a) 0°, (b) 60°, and (c) 70°. Note that the B-field scale shown on the abscissa of each panel increases with increasing tilt angle θ. (d) The data of (a)–(c) have been plotted vs $B\cos(\theta)$ in order to show that the characteristic field B_f and period of the radiation-induced oscillatory magnetoresistance are determined by the perpendicular component $B_\perp = B\cos(\theta)$ of the applied magnetic field B. (e) The values of the resistance R_{xx} at the peaks in plot (a), labeled (i), (ii), and (iii), have been plotted vs $\cos(\theta)$.

ence becomes consequential especially for the $\theta=90°$ case, which has therefore been denoted as $\theta \approx 90°$. An estimate of the effective tilt angle θ_{eff} was obtained from the data analysis, and these are also indicated at the appropriate point in the discussion. The electrical measurements were carried out using standard low-frequency ac lock-in techniques in an oversized condition for the waveguide (at 63 GHz), which implies an indeterminate microwave polarization. The microwave intensity was preset to an optimal value and remained undisturbed throughout the experiment.

III. RESULTS

Figure 1(a) shows the low-B transport under photoexcitation at 63 GHz with the specimen oriented at zero tilt angle, i.e., $\theta=0$ (see inset Fig. 1), such that the sample normal lies parallel to the applied magnetic field B. In all these measurements, the axis of propagation of the electromagnetic waves lies parallel to the magnetic field axis, and the electric field of the microwaves lies in the plane perpendicular to B. Figure 1(a) indicates a wide radiation-induced zero-resistance state in R_{xx} about $(4/5)B_f$, and a close approach to vanishing resistance at the next lower-B minimum, near $(4/9)B_f$, which follow the series $B=[4/(4j+1)]B_f$, with $j=1,2,3\ldots$. Here, $B_f = 2\pi f m^*/e$, m^* is the effective mass, e is the electron charge, and f is the radiation frequency.[1]

The effect of tilting the specimen with respect to the magnetic field is illustrated in Figs. 1(b) and 1(c). These figures indicate self-similarity in the oscillatory resistance pattern under tilt, provided that the magnetic field scale is increased appropriately with increasing tilt angle. Such data suggest that the characteristics field scale B_f in the absence of tilt, i.e., $\theta=0$, is mapped onto $B_f/\cos(\theta)$ at a finite tilt angle θ, reflecting a dependence of the underlying phenomena on $B_\perp = B\cos(\theta)$ [see Fig. 1(d)]. This plot, Fig. 1(d), exhibits data collapse and confirms that $B_\perp$ sets the characteristic field B_f and the inverse-magnetic-field periodicity B_f^{-1} of the radiation-induced resistance oscillations. The analysis indicated, in addition, a small difference between the preset tilt angle θ and the effective tilt angle θ_{eff} in the data, which is attributed here to an orientational uncertainty. Thus, we report that for $\theta=60°$, $\theta_{eff}=60.2°$, and for $\theta=70°$, $\theta_{eff}=69.7°$.

Although the oscillatory resistance traces show similarity under tilt when plotted versus $B_\perp$, there do occur some systematic variations in the data from one tilt angle to another. For example, a close comparison of Figs. 1(a)–1(c) indicates a nonmonotonic variation in the amplitude of the radiation-induced oscillations with increasing tilt angle [see Fig. 1(e)]. In particular, the resistance peak that has been labeled as (i) in Figs. 1(a) and 1(e) increases in height in going from Fig. 1(a) to 1(b), and then decreases in height from Fig. 1(b) to 1(c). We explain this effect as follows. It turns out that, in experiment, the oscillation peak amplitude initially increases, then saturates, and finally decreases with increasing radiation intensity.[1] In the experimental data shown in Fig. 1, the radiation intensity at $\theta=0°$ corresponds to an overexcited condition, a regime where the amplitude tends to decrease with increasing intensity. Such an overexcited condition was chosen for the $\theta=0°$ measurement in order to realize a significant photon flux on the 2DES even at the highest tilt angles. Thus, as the tilt angle is increased from $\theta=0°$ to 60°, the effective photon flux on the sample decreases, but this leads to a counterintuitive increase in the peak amplitude with increasing tilt angle [Figs. 1(a) and 1(b)]. Upon moving to the higher tilt angle $\theta=70°$ in Fig. 1(c), the oscillation peak amplitude (i) now decreases because this corresponds to the regime where a decrease in excitation intensity produces also a decrease in the oscillatory resistance amplitude.

The effect of increasing the tilt angle to nearly 90° is illustrated in Fig. 2, where we have compared the data traces obtained at $\theta=0°$ and $\theta \approx 90°$, with the $\theta \approx 90°$ data extending to 11.5 T, close to the maximum rated magnetic field of the superconducting magnet. Here, in Fig. 2(b), the weak oscillations in the vicinity of $B=4$ and 8 T are indicative of the virtual disappearance of the radiation-induced resistance oscillations and associated zero-resistance state in the $\theta \rightarrow 90°$ limit. Note that in this situation, essentially all of the applied magnetic field B appears as a component $B_\parallel$ in the plane of the 2DES. Here, the effective tilt angle extracted from the data is $\theta_{eff}=88.55°$.

At the outset, one tends to attribute such a reduction in the amplitude of the radiation-induced resistance oscillations in the large-tilt-angle limit to the vanishing photon flux on the 2DES, when the 2DES is oriented nearly parallel to the direction of microwave propagation. Yet, from the data of Fig. 2(b), it is difficult to rule out the alternate possibility that it is the application of a large parallel magnetic field $B_\parallel > 3$ T which plays some unforseen role in the quenching of the oscillations.

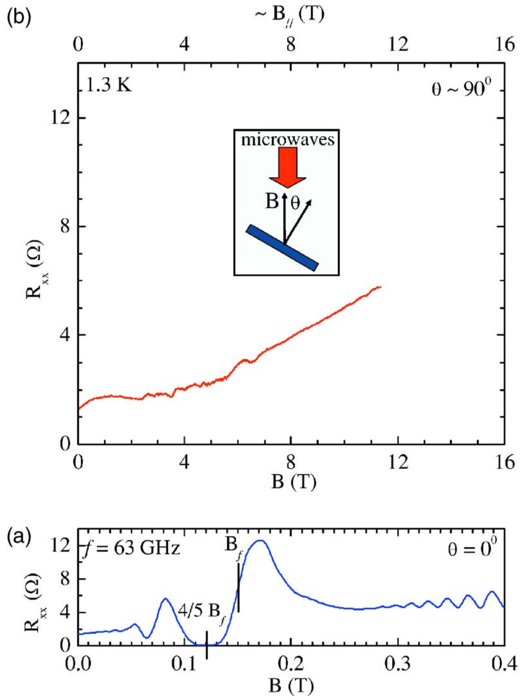

FIG. 2. (Color online) This figure compares the oscillatory photoinduced magnetoresistance characteristics observed at a tilt angle $\theta=0°$ (a) with the data obtained at $\theta\approx 90°$ (b). Note the enormously enhanced field scale for the $\theta\approx 90°$ case. These data suggest that the radiation-induced resistance oscillations vanish in the $\theta\rightarrow 90°$ limit.

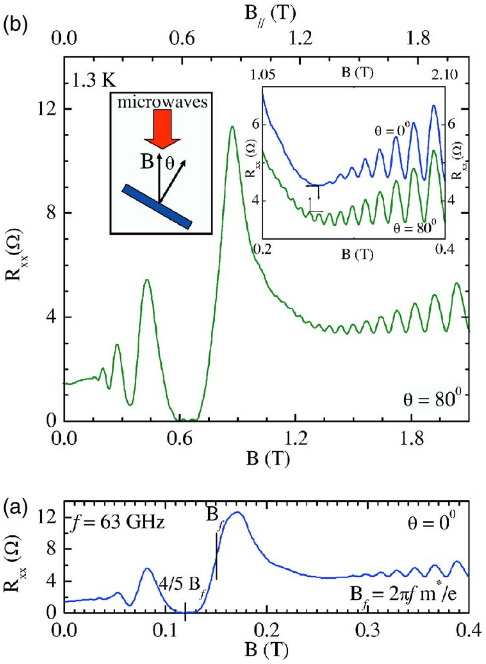

FIG. 3. (Color online) This figure compares the characteristics observed at a tilt angle $\theta=0°$ (a) with the data obtained at $\theta=80°$ (b). In (b), the component of the applied magnetic field that is parallel to the 2DES is indicated as $B_{\parallel}[=B\sin(\theta)]$ along the top abscissa. Note the similarity in the oscillatory traces at $\theta=0°$ and 80°. The right inset to (b) compares the SdH oscillations at $\theta=0°$ and 80°.

To address this point, we compare in Fig. 3 the data traces obtained at $\theta=0°$ and 80°. At $\theta=80°$, where the data suggest $\theta_{eff}=79°$, the $B_{\parallel}$ provided at the top abscissa of Fig. 3(b) indicates that a large fraction of the applied B appears as an in-plane component. Yet, the radiation-induced resistance oscillations continue to be observable at $\theta=80°$, with just a small reduction in the peak height in comparison to the $\theta=0°$ condition. From these data, it seems possible to conclude that, for the highest radiation-induced R_{xx} peak and the deepest R_{xx} valley, a parallel magnetic field component that lies between $0.6<B_{\parallel}<1.2$ T fails to extinguish the typical characteristics. Thus, such data support the hypothesis that the vanishing photon flux is the cause for the disappearance of the radiation-induced oscillatory resistance in the $\theta\rightarrow 90°$ limit in our tilted magnetic field experiments. In comparison, the amplitude of the oscillations in the 2D SdH effect is not expected to vanish in a similar $\theta\rightarrow 90°$ limit [see Ref. 19 and, for example, Figs. 1(d) and 3(b), right inset], although the B required to realize the associated oscillations becomes tremendously large in the large-tilt-angle limit.

IV. DISCUSSION

Here, we relate our observations to the recent report of a strong suppression of the radiation-induced zero-resistance states and associated magnetoresistance oscillations by a small parallel magnetic field $B_{\parallel}$.[20] As evident from Figs. 1–3, and especially Fig. 3, our data do not confirm that a modest $B_{\parallel}$, $B_{\parallel}\leqslant 0.5$ T, causes a strong suppression of the radiation-induced zero-resistance states and associated magnetoresistance oscillations. Although there are experimental differences between their two-axis magnet measurements[20] and our tilt field measurements, such differences seem unlikely to be the cause for the observed discrepancy. Perhaps the dissimilarities in observations are rooted in subtle differences in the physical environments between our respective specimens. For example, in the specimens utilized in Ref. 20, the onset of SdH oscillations moves to higher perpendicular magnetic fields with increasing $B_{\parallel}$. In comparison, the SdH data exhibited in the right inset of Fig. 3(b) seems not to indicate a similar shift of the SdH onset to higher $B_{\perp}$ with increasing θ. The shift of the SdH onset to higher perpendicular B in Ref. 20 could be a signature of an increase in the Landau level broadening in the presence of a parallel magnetic field. Plausibly, such a change in level broadening could then produce a chain reaction, including the observed disappearance of the radiation-induced zero-resistance states and associated resistance oscillations.[20] Yet, in such a scenario, it is not clear why a 50% increase in the field for the onset of SdH oscillations leads to the complete disappearance of the radiation-induced effects in Ref. 20.

It could also be that small differences in the physical environment become especially significant in the highest-mobility specimens, and that our lower mobility specimens provide for some stabilization against such perturbations. Further experimental studies appear necessary, however, to obtain further understanding of the observed discrepancy. At the moment, it appears that the parallel magnetic field component produces a variable response in the photoexcited 2DES.

V. SUMMARY

In summary, we have examined the effect of tilting a photoexcited high-mobility 2DES with respect to the applied magnetic field. We find that the characteristic field B_f and the inverse-magnetic-field periodicity of the radiation-induced magnetoresistance oscillations are determined by the component of the magnetic field that is perpendicular to the 2DES [Fig. 1(d)], as is typical for a 2D orbital effect. In addition, a parallel magnetic field component $B_{\|}$ in the range $0.6 < B < 1.2$ T at a tilt angle $\theta = 80°$ appears insufficient to quench the observed photoinduced oscillatory magnetoresistance. Yet, the radiation-induced resistance oscillations do disappear in the $\theta \rightarrow 90°$ limit, as the effective photon flux on the 2DES vanishes.

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[21] For this discussion, the characteristic field scale of the 2D Shubnikov–de Haas effect in the GaAs/Al$_x$Ga$_{1-x}$As system is the magnetic field that helps to realize the filling factor $\nu = 1$ condition, when the sample is oriented perpendicular to the magnetic field. As the sample is tilted by θ with respect to the applied B, the SdH oscillations span a larger B scale proportional to $\cos^{-1}(\theta)$, indicating that the SdH characteristic field scale is determined by $B_{\perp}$.