Radiation-induced oscillatory magnetoresistance as a sensitive probe of the zero-field spin-splitting in high-mobility GaAs/Al$_x$Ga$_{1-x}$As devices

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We suggest an approach for characterizing the zero-field spin splitting of high mobility two-dimensional electron systems, when beats are not readily observable in the Shubnikov–de Haas effect. The zero-field spin splitting and the effective magnetic field seen in the reference frame of the electron are evaluated from a quantitative study of beats observed in radiation-induced magnetoresistance oscillations

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The recent discovery[1] of novel nonequilibrium zero-resistance states under photoexcitation might be counted as the latest surprise in the physics of the two-dimensional electron system (2DES),[1,2] which has provided topics of enduring interest such as the integral and fractional quantum Hall effects (QHE).[3] Unlike quantum Hall systems, where zero-resistance states coincide with a quantized Hall effect,[3,4] these new states are characterized by an ordinary Hall effect in the absence of backscattering.[1,2] The remarkable phenomenology[1,2] has generated much excitement due to the possibility of identifying a new mechanism for artificially inducing vanishing electrical resistance, while obtaining a better understanding of QHE plateau formation and zero resistance in the 2DES.[5,6]

While the reasons mentioned above have motivated theoretical interest,[6] one might wonder whether the phenomena might also serve as an improved probe in a 2D problem with a functional interest. Here, we suggest that radiation-frequency-independent beats observed in the microwave-induced magnetoresistance might serve as a sensitive indicator of the zero-field spin splitting and the associated spin-orbit ‘‘Zeeman magnetic field’’ in the 2DES. The resulting technique could help to advance research involving the measurement, control, and utilization of the effective magnetic field that appears in the reference frame of the electron, in the high mobility GaAs/Al$_x$Ga$_{1-x}$As 2DES.[7,8]

Mobile 2D electrons can experience, in their rest frame, an effective magnetic field that develops from a normal electric field at the semiconductor heterojunction interface due to the so-called Bychkov-Rashba effect.[9] As this magnetic field can, in principle, be controlled by an electrical gate, it has been utilized in the design of novel spin based devices.[8] The Bychkov-Rashba term, proportional to the electron wave vector k, is believed to account for most of the observed zero-field spin splitting (ZFSS) in the narrow gap 2DES.[8] In the 2DES realized in wider gap GaAs/Al$_x$Ga$_{1-x}$As, a bulk inversion asymmetry (BIA) contribution to the ZFSS, provides an additional effective magnetic field as $B\rightarrow 0$.[10–14] Although theory has suggested that the BIA term is stronger than the Bychkov-Rashba term in the GaAs/Al$_x$Ga$_{1-x}$As heterostructure 2DES,[14] ZFSS in n type GaAs/Al$_x$Ga$_{1-x}$As is not easily characterized because its signature is often difficult to detect using available methods. This has hindered spintronics research in the GaAs/Al$_x$Ga$_{1-x}$As system, which provides the highest mobility 2DES.

Typical investigations of ZFSS in the 2DES look for beats in the Shubnikov–de Haas (SdH) oscillations that originate from dissimilar Fermi surfaces for spin-split bands.[15–17] However, the applicability of this approach requires the observability of SdH oscillations at very weak magnetic fields. In GaAs/Al$_x$Ga$_{1-x}$As heterostructures with two dimensional electrons, this is not easily realized, even in high quality material. In addition, other mechanisms can, in principle, provide similar experimental signatures.[16–18] Thus, a need has existed for simple new methods of investigating the spin-orbit interaction in the 2DES characterized by a small zero-field spin splitting, to supplement the SdH, Raman scattering, electron-spin resonance (ESR) and weak-localization based approaches.[16,19–21] In this light, the approach proposed here has the advantages of simplicity and improved sensitivity because the ZFSS ($\approx 20\ \mu$eV) is determined through a comparison of the spin splitting with an easily tunable, small energy scale set by the photon energy ($\approx 200\ \mu$eV), unlike, for example, the SdH approach which relates the ZFSS ($\approx 20\ \mu$eV) to differences between two (spin-split) Fermi surfaces with energy of order $E_F \approx 10$ meV in GaAs/Al$_x$Ga$_{1-x}$As.

Experiments were carried out on standard GaAs/Al$_x$Ga$_{1-x}$As heterostructure devices. Upon slow cooling in the dark, the 2DES exhibited a low electron density $n(4.2\ \mathrm{K}) \approx 1.5\times 10^{11}\ \mathrm{cm}^{-2}$. Subsequent brief illumination by a light-emitting diode (LED) produced $n(4.2\ \mathrm{K}) \approx 3\times 10^{11}\ \mathrm{cm}^{-2}$ and a mobility $\mu(1.5\ \mathrm{K})$ up to $1.5\times 10^{7}\ \mathrm{cm}^2/\mathrm{Vs}$. Lock-in based four-terminal measurements of the resistance and the Hall effect were carried out with the sample mounted inside a waveguide, as it was excited with microwaves over the frequency range $27 \leqslant f \leqslant 120$ GHz. The microwave power, estimated to be less than 1 mW, was set at the source and then reduced using variable attenuators.

Figure 1(a) illustrates the magnetoresistance R_{xx} observed with (w/) and without (w/o) microwave excitation, in the

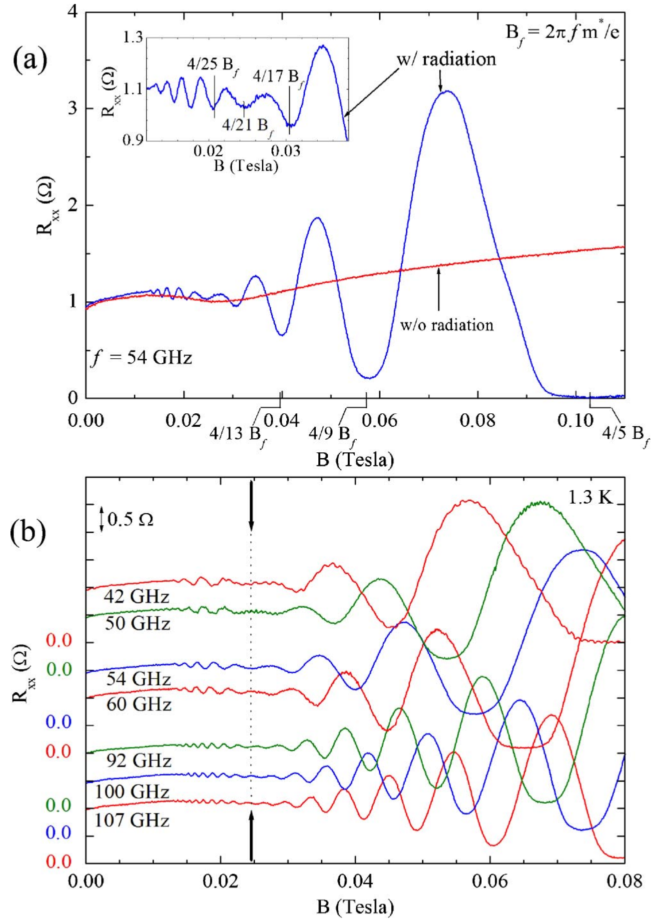

FIG. 1. (Color online) (a): The magnetoresistance R_{xx} in a GaAs/Al$_x$Ga$_{1-x}$As heterostructure with (w/) and without (w/o) microwave excitation. With radiation, R_{xx} minima occur about $B = [4/(4j+1)]B_f$, and follow this empirical rule through the beat, see inset. (b) R_{xx} oscillations are shown for a set of f. The beat remains fixed at $B \approx 0.024$ T as the R_{xx} oscillation frequency changes with f.

high mobility condition. Without radiation, weak magnetoresistance is characterized by the absence of the SdH effect to $B = 0.11$ T at 1.3 K. [see Fig.1(a)]. Excitation of the specimen with electromagnetic waves induces oscillations in R_{xx},[22,23] and a zero-resistance state over a broad B interval in the vicinity of 0.1 T.[1,2] Figure 1(a) shows that the three deepest resistance minima occur about $(4/5)B_f$, $(4/9)B_f$, and $(4/13)B_f$, where $B_f = 2\pi f m^*/e$. In addition, a nonmonotonic variation in the amplitude of the resistance oscillations produces a beat at low B [see Fig. 1(a), inset].[2] In Fig. 1(b), resistance data are shown for a number of microwave frequencies. These data show, for the first time, that the beat in the oscillatory resistance remains at a fixed B with a change in f.

A line shape study was carried out in order to characterize these oscillations. Over a narrow B window above the beat, the data could be fit with an exponentially damped sinusoid: $R_{xx}^{osc} = A' \exp(-\lambda/B)\sin(2\pi F/B - \pi)$, where A' is the amplitude, λ is the damping factor, and F is the resistance oscillation frequency.[22] A line shape that included the superposition of two such wave forms:

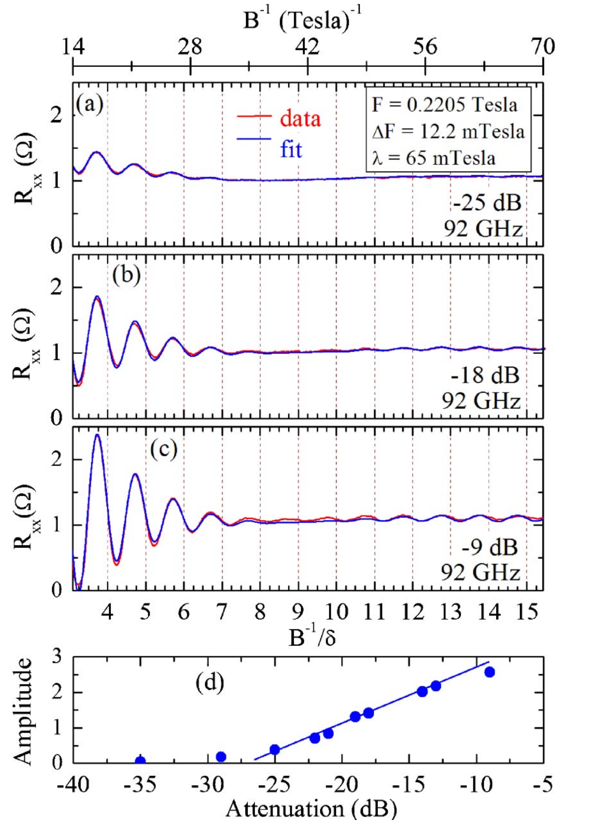

FIG. 2. (Color online) (a)–(c) R_{xx} oscillations are exhibited vs B^{-1} (top axis) and B^{-1}/δ (bottom axis) with the power attenuation factor as the parameter. Note that δ is the period in B^{-1}, i.e., $\delta = F^{-1}$, where F is determined through a fit (see text). (d) The fit-amplitude A of the R_{xx} oscillations is plotted vs the power attenuation factor in decibels.

$R_{xx}^{osc} = A' \exp(-\lambda/B)[\sin(2\pi F_1/B - \pi) + \sin(2\pi F_2/B - \pi)] = A\exp(-\lambda/B)\sin(2\pi F/B - \pi)\cos(2\pi\Delta F/B)$, where $F = (F_1 + F_2)/2$ and $\Delta F = (F_1 - F_2)/2$, proved unsatisfactory in modeling the beat data because this line shape includes a phase reversal through the beat, unlike experiment. Thus, we consider $R_{xx}^{osc} = A\exp(-\lambda/B)\sin(2\pi F/B - \pi)[1 + \cos(2\pi\Delta F/B)]$, which can realize beats without phase reversal.

Figures 2(a)–2(c) illustrate data obtained at a fixed f, as a function of the power attenuation factor. Also shown, is a fit to the data, using the line shape $R_{xx}^{osc} = A\exp(-\lambda/B)\sin(2\pi F/B - \pi)[1 + \cos(2\pi\Delta F/B)]$. Inspection shows good agreement between data and fit, and a comparison of Figs. 2(a), 2(b), and 2(c) shows a monotonic increase in the amplitude of the oscillations with increasing power level, that is reproduced by the fit parameter A, see Fig. 2(d). The oscillation period δ, where $\delta = 1/F$, served to renormalize the inverse field axis, as in the lower abscissa, see Fig. 2(c). The data plot vs B^{-1}/δ shows that nodes occur in the vicinity of $B^{-1}/\delta = j$, and $B^{-1}/\delta = j + 1/2$, where $j = 1,2,3,\ldots,$ while R_{xx} minima transpire about $B^{-1}/\delta = [4/(4j+1)]^{-1}$.

Representative data and fit at a pair of f, see Fig. 3, show that this line shape also describes the data obtained at widely spaced f. A summary of the fit parameters F, ΔF, and λ is

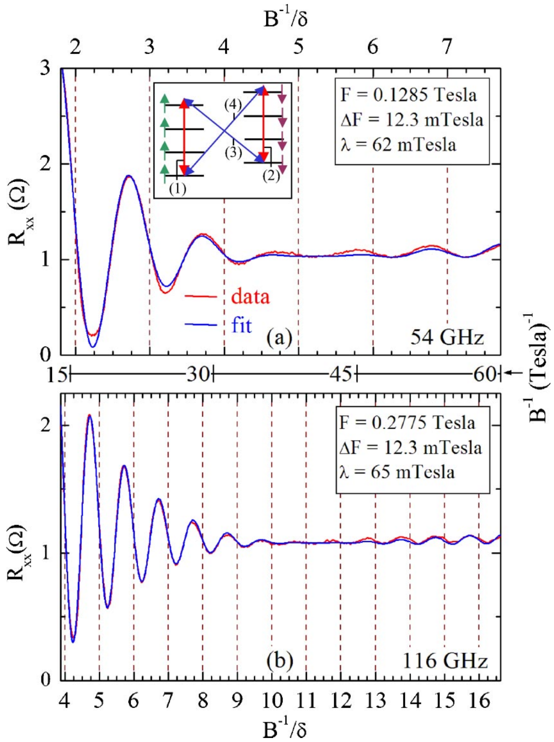

FIG. 3. (Color online) R_{xx} oscillations are shown at (a) 54 GHz and (b) 116 GHz, along with a fit (see text). The bottom and top axis show B^{-1}/δ, where $\delta = F^{-1}$. Inset to (a): The line-shape fit includes the contributions cartooned here. As $B \to 0$, a zero-field spin splitting produces an energy shift between the spin-up and spin-down levels.

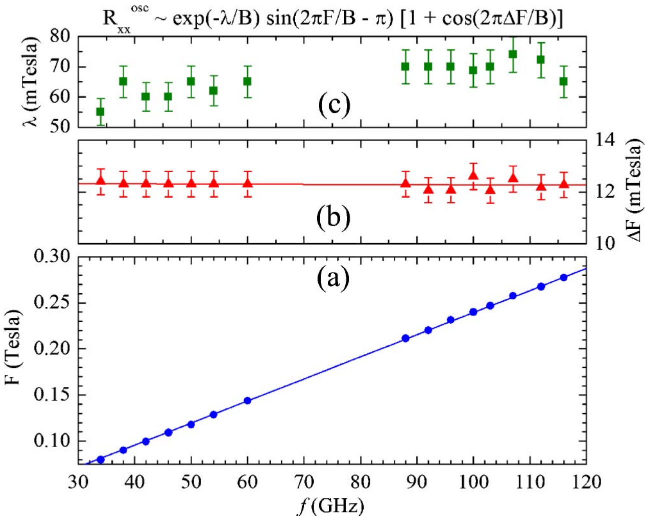

FIG. 4. (Color online) Fit parameters obtained from this line-shape study of the R_{xx} oscillations. (a) The resistance oscillation frequency F increases linearly with the radiation frequency. (b) The beat frequency ΔF is independent of f, and $\Delta F \approx 12.3$ mT. (c) The damping parameter λ appears to be independent of f.

presented in Fig. 4. The noteworthy features in Fig. 4 are: (i) F increases linearly with f, [see Fig. 4(a)].[1] (ii) The beat frequency $\Delta F \approx 12.3$ mT is independent of f [see Fig. 4(b)], consistent with Fig. 1(b). (iii) The damping parameter λ, $\lambda \approx 65$ mT, is also approximately independent of f [see Fig. 4(c)]. Here, the exponential damping could be rewritten in a Dingle form, $\exp(-\lambda/B) = \exp(-\pi/\omega_C \tau_f) \approx \exp(-pT_f/B)$, where T_f and t_f represent a finite frequency broadening temperature and lifetime, respectively, and p is approximately 1. Note that $\lambda = 65$ mT [Fig. 4(c)] corresponds to $T_f = 66$ mK.[22]

The line shape, $R_{xx}^{osc} = A\exp(-\lambda/B)\sin(2\pi F/B - \pi)[1 + \cos(2\pi\Delta F/B)]$, in our model can be understood by invoking four distinct transitions between Landau subbands near the Fermi level, as cartooned in the inset of Fig. 3. Here, the spin-orbit interaction helps to remove the spin degeneracy of Landau levels as $B \to 0$. Thus, the terms (1) and (2) represent spin preserving inter Landau level transitions, and the terms (3) and (4) represent spin-flip transitions. If the oscillations originating from these terms have equal amplitude and share the same λ, then one expects a superposition of four terms: $R_{xx}^{osc} = A'\exp(-\lambda/B)[\sin(2\pi F/B - \pi) + \sin(2\pi F/B - \pi) + \sin(2\pi[F - \Delta F]/B - \pi) + \sin(2\pi[F + \Delta F]/B - \pi)] = A\exp(-\lambda/B)\sin(2\pi F/B - \pi)[1 + \cos(2\pi\Delta F/B)]$, which is the line shape that has been used here.

Here, the nearly equal amplitudes for the spin-flip and the spin-preserving transitions are attributed to the occurrence of mechanisms such as the Bychkov-Rashba effect and the bulk-inversion asymmetry,[9,11] which produce spin precession about an in-plane magnetic field.[24] Under the influence of such spin-orbit mechanisms, the effective magnetic-field direction experienced by electrons changes with scattering, and this changing magnetic-field environment helps to modify spin orientation with respect to the applied magnetic field. A component of the microwave magnetic field, which is oriented perpendicular to the static magnetic field, can also serve to flip spin.

Thus, beats observed in the radiation-induced resistance oscillations appear as a consequence of a zero-field spin splitting, due to the spin-orbit interaction.[8–17,19,20] One might relate ΔF to the ZFSS by identifying the radiation-frequency change Δf that will produce a similar change in F, i.e., $\Delta f = \Delta F/[dF/df]$, where ΔF is the beat frequency, and dF/df is the rate of change of F with the radiation frequency [see Fig. 4(a)]. Then, the ZFSS corresponds to $\Delta f = 5.15$ GHz or $E_S(B=0) = h\Delta f = 21$ μeV. From a study of the ESR at high magnetic fields, Stein *et al.*[20] reported a ZFSS of 7.8 GHz for $n = 4.6 \times 10^{11}$ cm^{-2}, which complements our result for $n \approx 3 \times 10^{11}$ cm^{-2}. Theory suggests that, in the GaAs/Al$_x$Ga$_{1-x}$As heterostructure 2DES, both the BIA and the Bychkov-Rashba terms have similar magnitudes, even as the BIA makes the stronger contribution; the upper bound for the total ZFSS is ≈ 80 μeV.[14]

Our ESR study near filling factor $\nu = 1$ in the quantum Hall regime showed that the electron-spin resonance field, B_{ESR}, varied as $dB_{ESR}/df = 0.184$ T/GHz, which implies an effective Zeeman magnetic field $B_Z = (dB_{ESR}/df)\Delta f = 0.95$ T. As the effective magnetic field due to the Rashba term is oriented perpendicular to both the direction of electron motion and the normal of the 2DES, while the BIA contribution lies along the direction of motion of electrons,[14] this evaluation of B_Z is associated with the magnitude of the vector obtained by adding these terms. Although this estimate for the $B \rightarrow 0$ Zeeman magnetic field appears, at first sight, to be rather large by laboratory standards, the small g factor in GaAs/Al_xGa_{1-x}As heterostructures implies a small corresponding spin splitting, $E_S = 21\ \mu$eV, in comparison to the Fermi energy (≈ 10 meV). Thus, SdH beats would be expected below the lowest $B(\approx 0.2$ T at 1.3 K) at which SdH oscillations were observed in this material.

In summary, we have suggested that beats in the radiation-induced magnetoresistance oscillations in GaAs/Al_xGa_{1-x}As 2DES heterostructures might serve as a new probe of the zero-field spin splitting in the 2DES. This method could serve to simply track changes in the spin-orbit interaction that result from the controlled modification of the device structure, and this might prove helpful for spintronics research based in the GaAs/Al_xGa_{1-x}As system.[7,8]

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