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Radiation-induced oscillatory Hall effect in high-mobility GaAs/Al$_x$Ga$_{1-x}$As devices

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We examine the radiation induced modification of the Hall effect in high-mobility GaAs/Al$_x$Ga$_{1-x}$As devices that exhibit vanishing resistance under microwave excitation. The modification in the Hall effect upon irradiation is characterized by (a) a small reduction in the slope of the Hall resistance curve with respect to the dark value, (b) a periodic reduction in the magnitude of the Hall resistance R_{xy} that correlates with an increase in the diagonal resistance R_{xx}, and (c) a Hall resistance correction that disappears as the diagonal resistance vanishes.

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Vanishing electrical resistance has served to introduce new physical phenomena in condensed matter physics such as, for example, quantum Hall effects (QHE), which stemmed from the studies of zero-resistance states at low temperatures (T) and high magnetic fields (B) in the two-dimensional electron system (2DES).[1,2] Recently, the high-mobility 2DES provided an unexpected surprise by exhibiting novel zero-resistance states upon irradiation by low-energy photons. In this instance, vanishing diagonal resistance occurred about $B=(4/5)B_f$ and $B=(4/9)B_f$, where $B_f=2\pi f m^*/e$, m^* is an effective mass, e is the electron charge, and f is the radiation frequency, while the resistance minima followed the series $B=[4/(4j+1)]B_f$ with $j=1,2,3,\ldots$.[3] Remarkably, vanishing resistance induced by microwave excitation of the 2DES did not produce plateaus in the Hall resistance, although the diagonal resistance exhibited activated transport and zero-resistance states, similar to QHE.[3,4] These striking features have motivated substantial theoretical interest in this phenomenon.[5–10]

It is well known from the experimental studies of transport that the changes in the diagonal conductivity σ_{xx} such as those induced by the radiation in this context, can produce small corrections, in the strong field limit, in the Hall resistivity ρ_{xy}, via the tensor relation $\rho_{xy}=\sigma_{xy}/(\sigma_{xx}^2+\sigma_{xy}^2)$.[11] Durst and co-workers have also mentioned the possibility of an oscillatory Hall effect from their theoretical perspective.[7] Experimental results reported here examine in detail a radiation-induced modification of the Hall effect, which occurred in Fig. 1(b) of the article from the year 2002 of Ref. 3 and Fig. 1(b) of Ref. 12. In particular, it is demonstrated that microwave excitation changes the slope of the Hall resistance R_{xy} vs B curve by $\leqslant 1.5\%$. Further, there appears to be an oscillatory variation in R_{xy}, where a reduction, in magnitude, of the Hall resistance correlates with an increase in the diagonal resistance R_{xx}. It is also demonstrated that the correction to the Hall resistance disappears as $R_{xx}\rightarrow 0$. Finally, the oscillatory variation in the Hall resistance is comparable, in magnitude, to the radiation-induced change in the diagonal resistance, although the change ΔR_{xy} is small ($\leqslant 5\%$) in comparison to R_{xy}.

Measurements were performed on standard devices fabricated from GaAs/Al$_x$Ga$_{1-x}$As heterostructure junctions. After a brief illumination by a red light-emitting diode, the best material was typically characterized by an electron density, $n(4.2\text{ K})\approx 3\times 10^{11}\text{ cm}^{-2}$, and an electron mobility $\mu(1.5\text{ K})\approx 1.5\times 10^7\text{ cm}^2/\text{V s}$. Lock-in based four-terminal electrical measurements were carried out with the sample mounted inside a waveguide and immersed in pumped liquid He-3 or He-4, as the specimens were excited with electromagnetic (EM) waves in the microwave part of the spectrum, $27\leqslant f\leqslant 170$ GHz. In this report, we illustrate the characteristics of the radiation-induced modification of the Hall effect and point out a similarity to the situation in the quantum Hall limit.

Figure 1(a) shows measurements of the diagonal (R_{xx}) and Hall (R_{xy}) resistances where, under microwave excitation at 50 GHz, R_{xx} and R_{xy} exhibit the usual quantum Hall behavior for $B\geqslant 0.3$ T.[1,2] In contrast, for $B<0.25$ T, see inset of Fig. 1(a), a radiation-induced signal occurs and the resistance vanishes over a broad B interval about $B=0.1$ T. Further high-resolution measurements are shown in Fig. 1(b). Without EM-wave excitation, R_{xx} exhibits Shubnikov–de Haas (SdH) oscillations for $B>100$ mT [Fig. 1(b)]. The application of microwaves induces resistance oscillations, which are characterized by the property that the R_{xx} under radiation falls below the R_{xx} without radiation, over broad B intervals.[3,4,12] Indeed, R_{xx} appears to vanish about $(4/5)B_f$.[3] Although these zero-resistance states exhibit a flat bottom as in the quantum Hall regime,[1,2] R_{xy} under radiation does not exhibit plateaus over the same B interval.

Yet, the R_{xy} data of Fig. 1(b) show perceptible oscillations in the Hall resistance that are induced by the radiation.[3,12,13] Indeed, an edgewise inspection of the data shows that there is an antisymmetric oscillatory component in R_{xy}, in addition to a small radiation-induced change in the slope of the Hall curve.[12] In order to highlight these changes in the Hall effect, the radiation-induced portion of the Hall resistance $\Delta R_{xy}=R_{xy}^{excited}-R_{xy}^{dark}$ is shown along with R_{xx} in Fig. 1(c). Here, R_{xy}^{dark} is the Hall resistance obtained without (w/o)

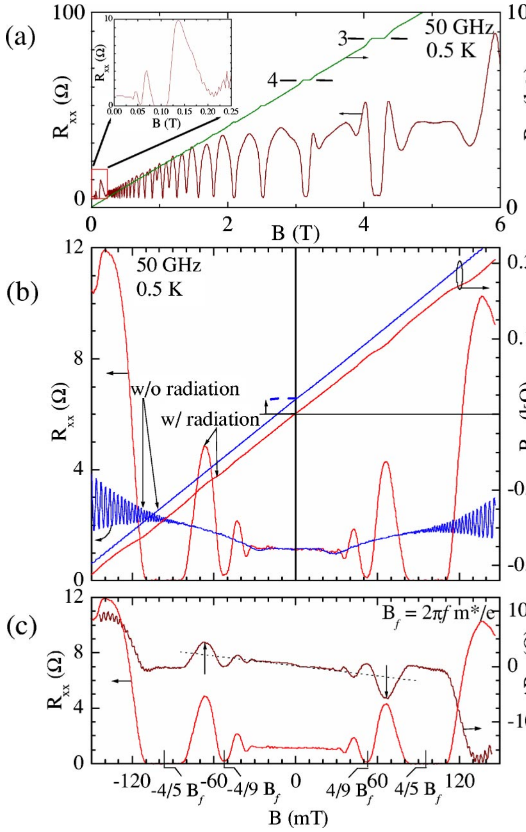

FIG. 1. (Color online) (a) The Hall (R_{xy}) and diagonal (R_{xx}) resistances are plotted vs the magnetic field B for a GaAs/Al$_x$Ga$_{1-x}$As device under excitation at 50 GHz. Quantum Hall effects (QHE) occur at high B as R_{xx} vanishes. (inset) An expanded view of the low-B data. (b) Data over low magnetic fields obtained both with (w/) and without (w/o) microwaves at 50 GHz. Here, radiation-induced vanishing resistance about (4/5)B_f does not produce plateaus in the Hall resistance, unlike in QHE. Yet, an edgewise inspection reveals that there are antisymmetric-in-B oscillations in R_{xy} that correlate with the R_{xx} oscillations. The w/o radiation Hall data have been offset here for the sake of clarity. (c) A comparison of the radiation-induced R_{xx} oscillations with the radiation-induced change ΔR_{xy} in the Hall resistance. Note the finite slope (dotted line) in ΔR_{xy}, and the odd symmetry under field reversal, which is characteristic of the Hall effect.

radiation, and $R_{xy}^{excited}$ is the Hall resistance with (w/) radiation. As this procedure for extracting the radiation-induced Hall resistance involves the subtraction of two large signals R_{xy}^{dark} and $R_{xy}^{excited}$ and since ΔR_{xy} is only a few percent of the dark Hall signal it is necessary to realize a stable low-noise experimental setup that minimizes parameter drifts with time in order to obtain noise-free reliable ΔR_{xy} data. The plot of Fig. 1(c) confirms a robust ΔR_{xy} signal. Indeed, the observed characteristics in Fig. 1(c), namely, a ΔR_{xy} signal that vanishes as $B \rightarrow 0$, and odd symmetry in ΔR_{xy} under field reversal, help to rule out the possibility that ΔR_{xy} originates from a mixture of the diagonal resistance with R_{xy}, as a result of a misalignment of the Hall voltage contacts. Further, the observation of quantized Hall effect in Fig. 1(a) under radiation, and the radiation-intensity-independence of the period of the radiation-induced oscillations, helps to rule out parallel conduction as the origin of nonvanishing ΔR_{xy}. These resistances scale to resistivities with a scale factor of one.

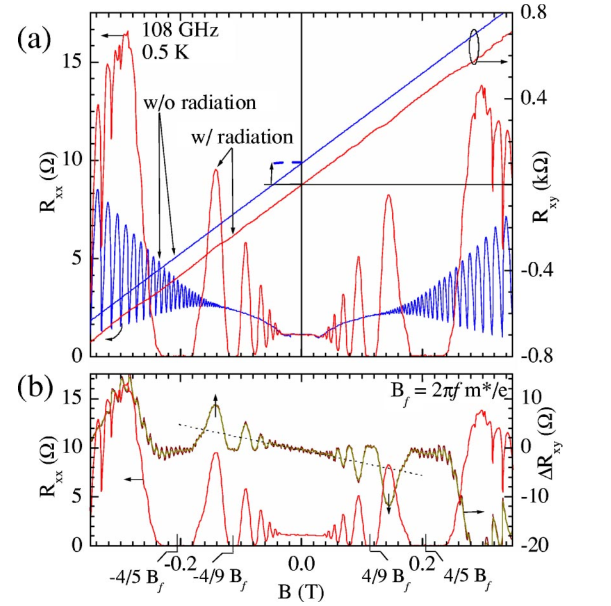

FIG. 2. (Color online) (a) Data over low magnetic fields obtained both with (w/) and without (w/o) radiation at 108 GHz. Here, once again, radiation-induced vanishing resistance about (4/5)B_f and (4/9)B_f does not produce plateaus in the Hall resistance, although antisymmetric-in-B oscillations in R_{xy} correlate with the R_{xx} oscillations. The slope of the R_{xy} is reduced by the radiation. The w/o radiation Hall data have been offset for the sake of clarity. (b) The radiation-induced portion of the Hall resistance ΔR_{xy} is shown along with R_{xx}. There is a slope to the ΔR_{xy} curve (dotted line) because the radiation reduces the slope of the Hall curve in (a). The correction to the Hall resistance ΔR_{xy} vanishes over the B interval of the R_{xx} zero-resistance states. Shubnikov–de Haas type resistance oscillations, which are observable in the ΔR_{xy} trace in the vicinity of the (4/5)B_f zero-resistance state, are attributed to the dark signal.

The data of Fig. 2 illustrate this same effect when the specimen is excited with microwaves at $f = 108$ GHz. In Fig. 2(a), the Hall data without radiation have been offset with respect to the Hall data with radiation in order to bring out the oscillatory portion of the Hall effect. Once again, an edgewise inspection of the irradiated R_{xy} data identifies an antisymmetric oscillatory Hall resistance, while it also reveals a small reduction in the slope of the Hall resistance. A comparison of Fig. 2(a) with Fig. 2(b) shows clearly that R_{xy} is reduced in magnitude over the B intervals where R_{xx} is enhanced by the radiation. On the other hand, as the diagonal resistance vanishes upon microwave excitation, as in the vicinity of $B = (4/5)B_f$, for example, the correction ΔR_{xy} also vanishes. The dotted line in the plot of ΔR_{xy} in Fig. 2(b) also confirms that there is an approximately 1.5% reduction in the slope of R_{xy} that is induced by the radiation. The small field reversal asymmetry that is observable in the w/ radiation R_{xx} data of Fig. 2 could be related to this radiation-induced change in the slope of R_{xy}. All these features are also observable in Figs. 1(b) and 1(c). Our studies indicate that the

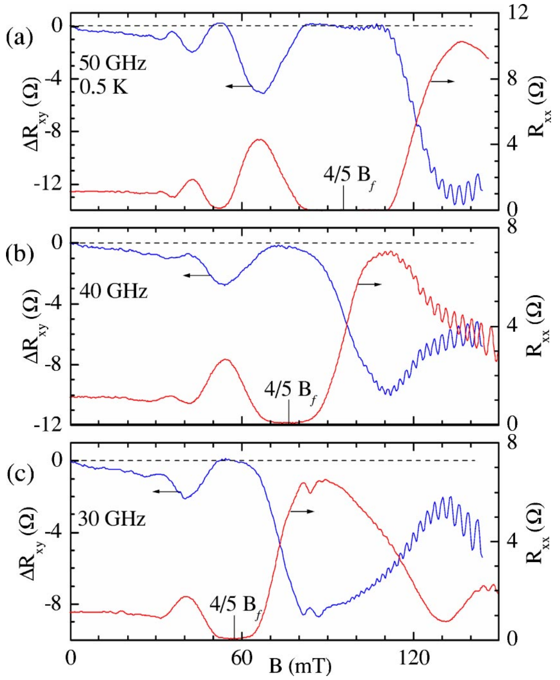

FIG. 3. (Color online) The radiation-induced change in the Hall resistance ΔR_{xy} is shown on the left ordinate and the diagonal resistance R_{xx} is shown on the right ordinate for microwave excitation at (a) 50 GHz, (b) 40 GHz, and (c) 30 GHz. Here, ΔR_{xy} tends to vanish as the diagonal resistance becomes exponentially small in the vicinity of $(4/5)B_f$. In addition, a finite slope is evident in ΔR_{xy} for $B \leqslant 30$ mT, as in Figs. 1(c) and 2(b).

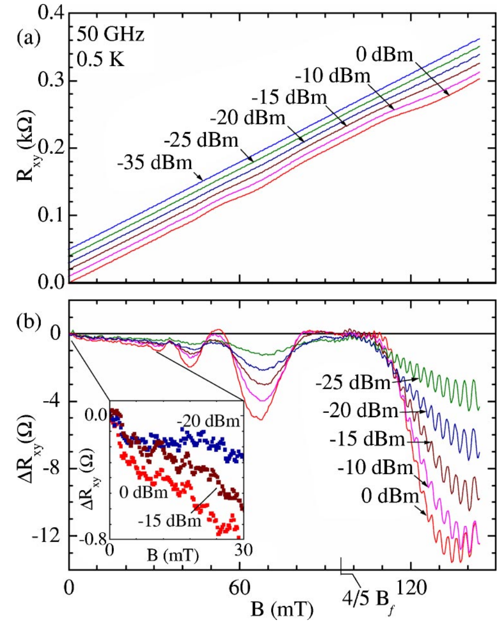

FIG. 4. (Color online) (a) The Hall resistance R_{xy} is shown as a function of the magnetic field B for radiation intensities, given in units of dBm. The data indicate progressively stronger modulations in R_{xy} with increased radiation intensity. Data have been offset for the sake of clarity. (b) This plot shows the radiation-induced change in the Hall resistance ΔR_{xy} obtained from the data of (a). The inset illustrates the B dependence of ΔR_{xy} for $B \leqslant 30$ mT.

radiation induced reduction in the slope of the Hall curve brings with it a corresponding small shift (at the percent level) in the positions of the extrema in the SdH oscillations to higher magnetic fields. A straightforward interpretation suggests that the change in the R_{xy} slope, and the shift of the SdH extrema, result from a radiation-induced change in the cross-sectional area of the Fermi surface.

Figure 3 illustrates the frequency dependence, and the correlation between ΔR_{xy} and R_{xx}, at microwave frequencies $f=30$, 40, and 50 GHz. Here, and also in Fig. 4, the exhibited Hall resistances represent an antisymmetric combination of the signal obtained for the two directions $(+B, -B)$ of the magnetic field. In each case shown in Fig. 3, it is observed that (a) the magnitude of ΔR_{xy} is approximately the same as the magnitude of R_{xx}, (b) an increase in R_{xx} under microwave excitation leads to a decrease in the magnitude of R_{xy}, i.e., $\Delta R_{xy} \leqslant 0$ for $B \geqslant 0$, (c) ΔR_{xy} shows a finite slope as $B \rightarrow 0$, and (d) the correction ΔR_{xy} vanishes as the diagonal resistance vanishes in the vicinity of $B=(4/5)B_f$. These data also confirm that the characteristic field scale for the oscillatory Hall effect follows the microwave frequency in the same way as R_{xx}.

We exhibit the power dependence of the Hall resistance at a fixed microwave frequency in Fig. 4. Figure 4(a) shows R_{xy} for various microwave intensities in units of dBm, with 0 dBm$=1$ mW. Here, it is evident that increasing the radiation power produces progressively stronger variations in R_{xy}. This is confirmed by Fig. 4(b), which demonstrates that the minima in ΔR_{xy} become deeper with increased power, consistent with the results of Figs. 1(c), 2(b), and 3.

There appear to be some similarities between the Hall resistance correction reported here and the experimental observations under quantum Hall conditions. In the vicinity of integral filling factors in the quantum Hall situation, the measured Hall resistivity ρ_{xy} is expected to approach the quantum Hall resistance, $R_H(i)=h/(e^2 i)$, in the limit of vanishing diagonal resistivity, i.e., $\rho_{xx} \rightarrow 0$, at zero temperature.[14] At finite temperature, experiment has indicated corrections to the Hall resistivity that are proportional to the magnitude of the diagonal resistivity, $\Delta\rho_{xy} = -s\rho_{xx}$, with s a device-dependent constant.[14] That is, a finite (nonvanishing) ρ_{xx} can lead to a reduction in the magnitude of ρ_{xy}. This is analogous to the effect reported here since an increase in R_{xx} due to microwave excitation leads also to a decrease in the magnitude of the Hall resistance, i.e., $\Delta R_{xy} \sim -R_{xx}$ in Fig. 3, and, as the R_{xx} vanishes, so does the correction to the Hall resistance. Indeed, experiment suggests some device dependence to this radiation-induced Hall resistance correction just as in the quantum Hall situation.[14] Thus, one might suggest that increased backscattering due to the radiation,[5,7,9] leads to an increased dissipative current over the R_{xx} peaks, which loads the Hall effect, similar to suggestions in Ref. 14. It might then follow that the suppression of the backscattered current over the R_{xx} minima, eliminates also the correction to the Hall effect in our experiment.

The radiation-induced change in the slope of the Hall curve appears to fall, however, outside the scope of this analogy, and this helps to identify the dissimilarities between the radiation-induced effect reported here and the quantum Hall situation: In the quantum Hall situation, the effect of finite temperature is to mainly increase the diagonal resistance, which leads to a decrease in the observed Hall resistance.[14] In the case of the radiation-induced resistance oscillations, the radiation, which plays here a role that is similar to the temperature in the quantum Hall situation, can serve to both increase and decrease the diagonal resistance. Theory would suggest the existence of both a downhill and uphill radiation-induced current with respect to the Hall field.[7] Naively, one might then expect both an enhancement and a diminishment of the magnitude of the Hall resistance if the quantum Hall analogy carried over to this case. Yet, we have found that the magnitude of R_{xy} is mainly reduced by the radiation. The radiation-induced change in the slope of the Hall resistance vs B seems to be essential to make it come out in this way. The results seem to hint at different transport pictures for the peaks and valleys of the radiation-induced oscillatory magnetoresistance.

In summary, high-mobility GaAs/$Al_xGa_{1-x}As$ devices that exhibit vanishing R_{xx} under microwave radiation also show a radiation-induced modification of the Hall effect. The modification is characterized by (a) a small reduction in the slope of the R_{xy} vs B curve upon microwave excitation, with respect to the dark value, (b) a reduction in the magnitude of the Hall resistance that correlates with an increase in the diagonal resistance R_{xx}. The radiation-induced changes in R_{xx} and R_{xy} are comparable in magnitude, although ΔR_{xy} is small compared to R_{xy}, and (c) a Hall resistance correction that disappears as the diagonal resistance vanishes. These features seem to provide new experimental insight into this remarkable phenomenon.[3–10,12,13,15]

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