

## Radiation-induced oscillatory Hall effect in high-mobility GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As devices

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We examine the radiation induced modification of the Hall effect in high-mobility GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>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).<sup>1,2</sup> 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  $B_f=2\pi fm^*/e$ ,  $m^*$  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  $j=1,2,3,\dots$ .<sup>3</sup> 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.<sup>3,4</sup> These striking features have motivated substantial theoretical interest in this phenomenon.<sup>5-10</sup>

It is well known from the experimental studies of transport that the changes in the diagonal conductivity  $\sigma_{xx}$  such as those induced by the radiation in this context, can produce small corrections, in the strong field limit, in the Hall resistivity  $\rho_{xy}$ , via the tensor relation  $\rho_{xy}=\sigma_{xy}/(\sigma_{xx}^2+\sigma_{xy}^2)$ .<sup>11</sup> Durst and co-workers have also mentioned the possibility of an oscillatory Hall effect from their theoretical perspective.<sup>7</sup> 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  $\leq 1.5\%$ . 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  $\Delta R_{xy}$  is small ( $\leq 5\%$ ) in comparison to  $R_{xy}$ .

Measurements were performed on standard devices fabricated from GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>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  $\mu(1.5\text{ K})\approx 1.5\times 10^7\text{ cm}^2/\text{Vs}$ . 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,  $27\leq f\leq 170\text{ GHz}$ . 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  $B\geq 0.3\text{ T}$ .<sup>1,2</sup> In contrast, for  $B<0.25\text{ T}$ , see inset of Fig. 1(a), a radiation-induced signal occurs and the resistance vanishes over a broad  $B$  interval about  $B=0.1\text{ T}$ . Further high-resolution measurements are shown in Fig. 1(b). Without EM-wave excitation,  $R_{xx}$  exhibits Shubnikov-de Haas (SdH) oscillations for  $B>100\text{ mT}$  [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.<sup>3,4,12</sup> Indeed,  $R_{xx}$  appears to vanish about  $(4/5)B_f$ .<sup>3</sup> Although these zero-resistance states exhibit a flat bottom as in the quantum Hall regime,<sup>1,2</sup>  $R_{xy}$  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.<sup>3,12,13</sup> 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.<sup>12</sup> In order to highlight these changes in the Hall effect, the radiation-induced portion of the Hall resistance  $\Delta R_{xy}=R_{xy}^{\text{excited}}-R_{xy}^{\text{dark}}$  is shown along with  $R_{xx}$  in Fig. 1(c). Here,  $R_{xy}^{\text{dark}}$  is the Hall resistance obtained without (w/o)

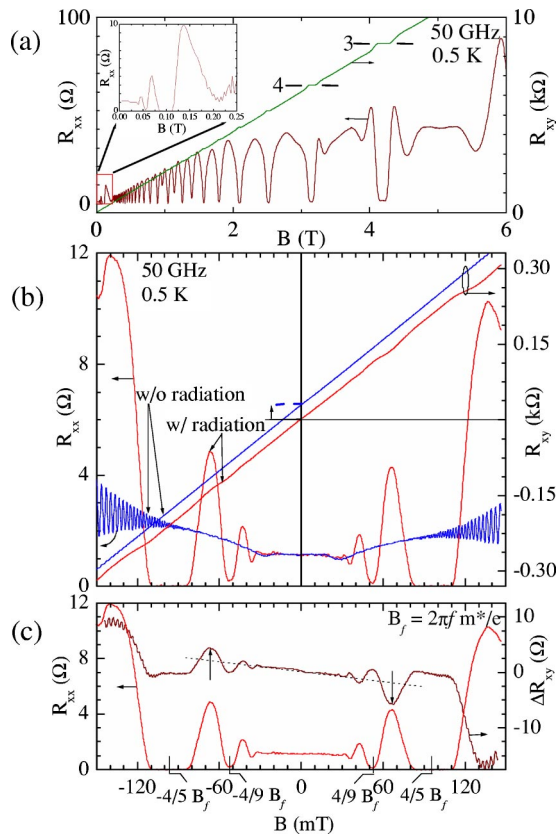


FIG. 1. (Color online) (a) The Hall ( $R_{xy}$ ) and diagonal ( $R_{xx}$ ) resistances are plotted vs the magnetic field  $B$  for a GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As device under excitation at 50 GHz. Quantum Hall effects (QHE) occur at high  $B$  as  $R_{xx}$  vanishes. (inset) An expanded view 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  $\Delta R_{xy}$  in the Hall resistance. Note the finite slope (dotted line) in  $\Delta R_{xy}$ , 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  $\Delta R_{xy}$  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  $\Delta R_{xy}$  data. The plot of Fig. 1(c) confirms a robust  $\Delta R_{xy}$  signal. Indeed, the observed characteristics in Fig. 1(c), namely, a  $\Delta R_{xy}$  signal that vanishes as  $B \rightarrow 0$ , and odd symmetry in  $\Delta R_{xy}$  under field reversal, help to rule out the possibility that  $\Delta R_{xy}$  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

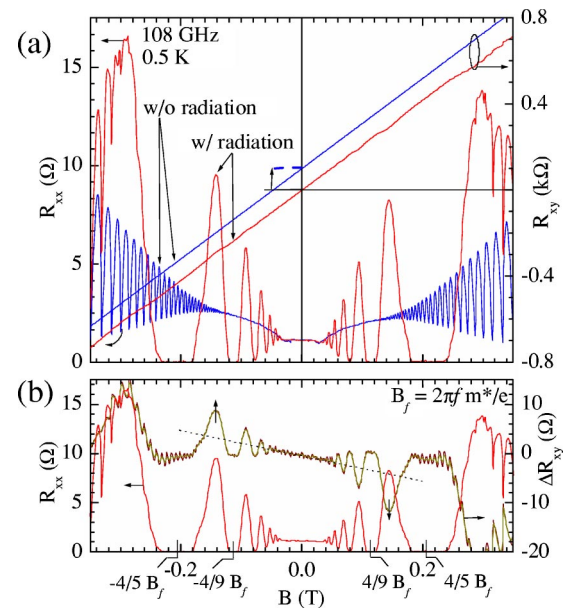


FIG. 2. (Color online) (a) Data over low magnetic fields obtained both with (w/) and without (w/o) microwave radiation at 108 GHz. Here, once again, radiation-induced vanishing resistance about  $(4/5)B_f$  and  $(4/9)B_f$  does not produce plateaus in the Hall resistance, although antisymmetric-in-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

out parallel conduction as the origin of nonvanishing  $\Delta R_{xy}$ . These resistances scale to resistivities with a scale factor of one.

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  $\Delta R_{xy}$  also vanishes. The dotted line in the plot of  $\Delta R_{xy}$  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

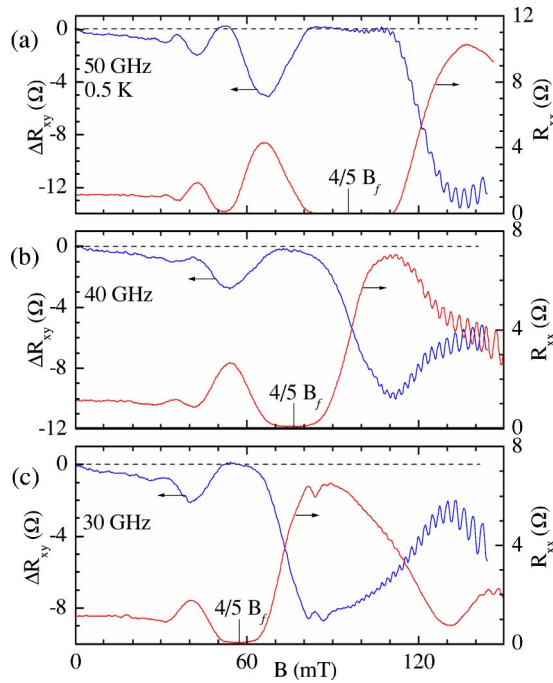


FIG. 3. (Color online) The radiation-induced change in the Hall resistance  $\Delta R_{xy}$  is shown on the left ordinate and the diagonal resistance  $R_{xx}$  is shown on the right ordinate for microwave excitation at (a) 50 GHz, (b) 40 GHz, and (c) 30 GHz. Here,  $\Delta R_{xy}$  tends to vanish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

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  $\Delta R_{xy}$  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  $\Delta R_{xy}$  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.,  $\Delta R_{xy} \leq 0$  for  $B \geq 0$ , (c)  $\Delta R_{xy}$  shows a finite slope as  $B \rightarrow 0$ , and (d) the correction  $\Delta R_{xy}$  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

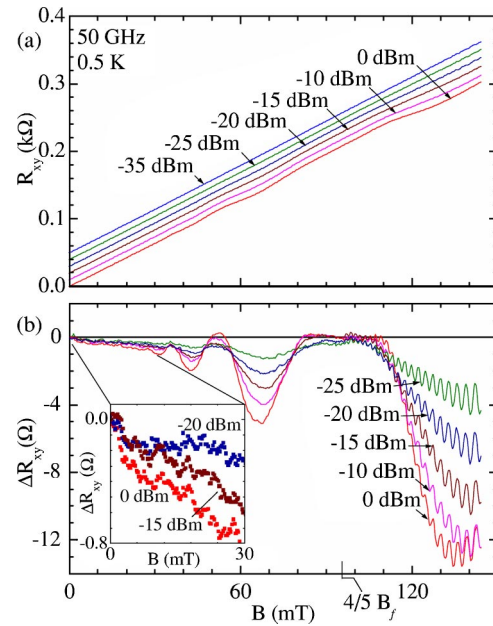


FIG. 4. (Color online) (a) The Hall resistance  $R_{xy}$  is shown as a function of the magnetic field  $B$  for radiation intensities, given in units of dBm. The data indicate progressively stronger modulations in  $R_{xy}$  with increased radiation intensity. Data have been offset for the sake of clarity.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

$R_{xy}$ . This is confirmed by Fig. 4(b), which demonstrates that the minima in  $\Delta R_{xy}$  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  $\rho_{xy}$  is expected to approach the quantum Hall resistance,  $R_H(i) = h/(e^2i)$ , in the limit of vanishing diagonal resistivity, i.e.,  $\rho_{xx} \rightarrow 0$ , at zero temperature.<sup>14</sup> 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.<sup>14</sup> That is, a finite (nonvanishing)  $\rho_{xx}$  can lead to a reduction in the magnitude of  $\rho_{xy}$ . 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.<sup>14</sup> Thus, one might suggest that increased backscattering due to the radiation,<sup>5,7,9</sup> 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.<sup>14</sup> 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.<sup>7</sup> 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<sub>x</sub>Ga<sub>1-x</sub>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  $\Delta R_{xy}$  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.<sup>3-10,12,13,15</sup>

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