Radiation-induced zero-resistance states with resolved Landau levels

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(Dated: March 23, 2022)

The microwave-photonexcited high mobility GaAs/AlGaAs two-dimensional electron system exhibits an oscillatory-magnetoresistance with vanishing resistance in the vicinity of magnetic fields

\[ B = \frac{4}{4j+1}B_f, \]

where \( B_f = 2\pi fm^*/e, \quad m^* \] is an en effective mass, \( e \) is the charge, \( f \) is the microwave frequency, and \( j = 1,2,3,... \]

Here, we report transport with well-resolved Landau levels, and some transmission characteristics.

Journal Reference: Appl. Phys. Lett. 85, 4962 (2004).

The experimental study of quantized Hall effect (QHE) has shown that a two-dimensional electron system (2DES) can exhibit zero-resistance states in the vicinity of integral and mostly odd-denominator fractional filling factors, at low temperatures, \( T \), and high magnetic fields, \( B \). These (quantum Hall) zero - resistance states are initially approached, at finite \( T \), following an activation law, which is understood as a manifestation of a gap in the electronic spectrum.[1] Recent observations of radiation-induced zero-resistance states in the 2DES are particularly interesting because they have shown that the above mentioned characteristics, i.e., activated transport and zero-resistance states, can also be obtained in a photo-excited high mobility 2DES, without realizing at the same time a QHE.[2, 3] In such a situation, one wonders whether the observed characteristics could once again be indicative of a spectral gap, as in the quantum Hall limit.[1]

The zero-resistance states of interest here are induced by microwave excitation of a high mobility GaAs/AlGaAs 2DES, at low \( T \), in a large filling factor limit.[2, 3, 4] Experiments indicate vanishing diagonal resistance, following an activation law, 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.[2] In this report, we illustrate transport with resolved Landau levels and transmission characteristics, as we refer the reader to the literature for discussions of theory.[5, 6]

Experiments were performed, as indicated elsewhere,[2] on standard devices fabricated from GaAs/AlGaAs heterostructure junctions with an electron mobility up to \( 1.5 \times 10^7 \) cm²/Vs. Typically, a specimen was mounted inside a waveguide, immersed in pumped liquid Helium, and irradiated with electromagnetic (micro-) waves over the frequency range \( 27 \leq f \leq 170 \) GHz. Reported electrical measurements were carried out using low frequency ac lock-in techniques, as usual.

Figure 1 shows the low-\( B \) transport under photoexcitation at 60 GHz. Fig. 1(a) indicates a wide \( R_{xx} \) radiation-induced zero-resistance state 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 \( j = 1,2,3,... \) A remarkable feature in these zero-resistance states is the absence of concomitant plateau formation in the Hall effect,[2, 3] as in typical quantum Hall systems.[1] The \( R_{xx} \) data of Fig 1(a) show, for example, that the Hall resistance increases linearly vs. the magnetic field and coincides with the \( R_{xx} \) that is observed without radiation over the \( B \) interval corresponding to the \( (4/5)B_f \) zero-resistance state. Yet, a careful comparison of the photoexcited (w/ radiation) Hall effect with the dark (w/o radiation) Hall effect reveals some definite modifications in \( R_{xx} \) upon irradiation. For example, at the \( R_{xx} \) maxima, there appear to be reductions in the magnitude of the irradiated \( R_{xx} \). In addition, well above \( B_f \), i.e., \( B \geq 0.2 \) Tesla, where \( R_{xx} \) exhibits QHE plateaus, a given filling factor QHE appears shifted to higher \( B \) under the influence of radiation. These effects could, however, be reversed simply by switching off the microwave excitation.

As suggested by Fig. 1, radiation-induced zero-resistance states are typically observed over a range of magnetic fields corresponding to weak- or non-existent SdH oscillations (in the dark) at easily accessible microwave frequencies and temperatures. A question that we wish to address is whether radiation-induced zero-resistance states can also occur over the range of \( B \) where the amplitude of SdH oscillations in the dark is relatively large, say substantially greater than one-half of the background dc resistance in the absence of microwave excitation, at the same \( B \).

We show here results which indicate that, indeed, these radiation-induced zero-resistance states can also occur in the \( B \) limit, where giant Shubnikov-de Haas oscillations are observable in the specimen. That is, where the Landau level spacing, \( h\omega_C \), exceeds both the thermal energy, \( k_B T \), and a broadening parameter, \( \Gamma \), defined from the transport relaxation time i.e., \( \Gamma << k_B T < h\omega_C \), which may be viewed as a quantum Hall threshold. This is a regime of consequence because theory has sometimes identified observed effects with the limit where \( \Gamma << k_B T \approx h\omega_C \).[6]

Fig. 2(a) shows that the dark specimen exhibits strong SdH oscillations over the range of \( B^{-1} \) given by \( 13 \leq
that the radiation reduces the background diagonal resistance and that in turn suppresses the amplitude of SdH oscillations. Here, we imagine that the background resistance (and resistivity) could be defined (and extracted) from the midpoints of the SdH oscillations. Here, at the examined temperature, $T = 0.5 K$, $h f = 0.676$ meV easily exceeds $k_B T = 0.043$ meV. Estimates of the broadening parameter indicate that $\Gamma << k_B T$.[2]

Photoexcitation of the specimen with $f = 163.5$ GHz radiation initially produces a modulation in the amplitude of the SdH oscillations (see Fig. 2(b)), which is the signature of the radiation-induced resistance oscillations in this separated Landau level limit. One might plausibly explain this SdH modulation feature, at least about the radiation induced resistance minima, by suggesting that the radiation reduces the background diagonal resistance, and that in turn suppresses the amplitude of SdH oscillations. Here, we imagine that the background resistance (and resistivity) could be defined (and extracted) from the midpoints of the SdH oscillations.

A further increase in the radiation intensity, see Fig. 2(c), leads to zero-resistance states over broad $B^{-1}$-intervals. For example, the $(4/5) B_f$ state occurs here about $B^{-1}/\delta_{SdH[Dark]} = 20$, and it looks similar to the effect that is observed at lower $f$ (see Fig. 1). Note that
at \((4/5)B_f\), \(\hbar \omega_c \approx (4/5)hf\) is noticeably greater than \(k_B T\). A remarkable feature in these data of Fig. 2(c) is that the SdH oscillations disappear as \(R_{xx} \rightarrow 0\) under the influence of radiation. It appears worth pointing out that we have not observed any evidence of "chopping" of the SdH minima on the approach to zero-resistance, as might be expected if the amplitude of the SdH oscillations did not appropriately follow the background \(R_{xx}\), or if the SdH amplitude somehow stayed constant as the background resistivity went to zero under microwave excitation.

It is also worth considering the SdH behavior outside of the domain of zero-resistance states. For example, on either side of the \((4/5)B_f\) zero-resistance state (about \(B^{-1}/\delta_{SdH[Dark]} = 29\) in Fig. 2(c), the amplitude of the SdH oscillations is not also increased, and this suggests a break in the correlation between the background resistance and the SdH amplitude at the maxima, unlike the case with the minima. A noteworthy point here seems to be that in Fig. 2(b) and (c), the SdH oscillations seem not to increase in amplitude under the influence of microwaves. The SdH amplitude either stays the same or it is reduced under microwave excitation. This might indicate a role for electron heating. Parenthetically, there is also some evidence that the threshold radiation intensity for realizing zero-resistance increases, as one moves to higher \(f\). Thus, heating could be more influential at higher excitation frequencies. This feature is attributed here to the point that, as the photon energy increases with \(f\), more power needs to be delivered to the specimen in order to maintain a constant photon number per unit of time, which could be the essential underlying parameter, at a higher \(f\). A subtle feature of interest in Fig. 2 is that the SdH extrema seem to shift to lower \(B^{-1}\) (or higher \(B\)) under microwave excitation, in qualitative agreement with the behavior observed in the Hall effect in Fig. 1(a).

The characteristic field scale for the radiation induced effect, \(B_f[2]\) suggests a possible relation to cyclotron resonance, which one might investigate through simultaneous transmission and transport measurements in the same high mobility specimen, see Fig. 3. Here (see Fig. 3(inset)), a resistance sensor placed immediately below the sample served to gauge the relative transmitted power. Fig. 3(a) illustrates the specimen \(R_{xx} vs. B\), while Fig. 3(b) exhibits the \(B\)-dependent sensor resistance, \(R_S\). In this GaAs/AlGaAs specimen, the optimal radiation induced \(R_{xx}\) response occurred in the vicinity of -9 dB, see Fig. 3(a). That is, the amplitude of the radiation-induced resistance oscillations increased monotonically with increasing power up to -9 dB. A further increase of the radiation intensity (dB \(\rightarrow 0\)) produced a "breakdown" or a reduction in the \(R_{xx}\) peak height along with an increase in the resistance at the minima (see Fig. 3(a)). The response of the transmission sensor, \(R_S\), (see Fig. 3(b)) suggests structure at magnetic fields about- and mostly above- \(B_f\), which becomes more pronounced with increased excitation. The feature correlates with a strong radiation-induced distortion of the \(R_{xx}\) peak that is centered about 0.3 Tesla. One might interpret some of these features about \(B_f\) as a signature of cyclotron resonance, although further supplementary evidence appears necessary to confirm this hypothesis. Remarkably, the observed oscillations in \(R_{xx}\) below \(B_f\) appear imperceptible in the sensor response (cf. Fig. 3(a) and Fig. 3(b)).

In summary, we have emphasized the possibility of realizing radiation induced zero-resistance states, see Fig. 2, in a range of \(B\) where \(R_{xx}\) exhibits giant SdH oscillations due to separated Landau levels. This result indi-
cates that radiation-induced zero-resistance states occur even outside a so-called quasi-classical limit. Transmission measurements also indicate non-monotonic features in the transmitted signal about and above $B_f$, some of which could be indicative of cyclotron resonance.

The authors acknowledge discussions with K. von Klitzing, V. Narayanamurti, J. H. Smet, and W. B. Johnson. The high mobility material was kindly provided by V. Umansky.

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