Radiation-induced zero-resistance states in GaAs/AlGaAs heterostructures: Voltage-current characteristics and intensity dependence at the resistance minima

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High mobility two-dimensional electron systems exhibit vanishing resistance over broad magnetic field intervals upon excitation with microwaves, with a characteristic reduction of the resistance with increasing radiation intensity at the resistance minima. Here, we report experimental results examining the voltage-current characteristics, and the resistance at the minima versus the microwave power. The findings indicate that a non-linear *V-I* curve in the absence of microwave excitation becomes linearized under irradiation, unlike expectations, and they suggest a similarity between the roles of the radiation intensity and the inverse temperature.

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I. INTRODUCTION

Vanishing resistance induced by electromagnetic wave excitation in the ultra-high-mobility two-dimensional electron system (2DES), at low temperatures (T) and modest magnetic fields (B), has suggested the possibility of novel non-equilibrium zero-resistance states (ZRS) in the 2DES.[1] Remarkably, in this effect, vanishing resistance does not produce plateaus in the Hall resistance, although the diagonal resistance exhibits activated transport and zero-resistance states, similar to quantum Hall effects (QHE).[1–5]

A surge in theory has already produced a physical framework for viewing this extraordinary phenomenon, with testable predictions for further experiment.[6–30] A class of hypothesis attributes radiation induced resistance oscillations to B-dependent enhancement/reduction of the current.[6,8,10,12] An oscillatory density-of-states, an electric field, and impurity scattering appear to be the key ingredients in theory, which indicates negative resistivity for sufficiently large radiation intensities.[6,8,12] The modeling by Durst and co-workers,[8] which is similar to the work by Ryzhii,[6] reproduced the period and, approximately, the phase reported in Ref. 1, although there was variance between theory and experiment so far as the realization of negative resistivity was concerned.[6,8] A possible physical instability for a negative resistivity state, meanwhile, led to the conjecture by Andreev *et al.* of a current dependent resistivity, and the formation of current domains, along with a scenario for realizing zero-resistance in measurement.[9] These works taken together seem to provide a path for realizing radiation-induced oscillatory magnetoresistance and zero-resistance.[6,8,9] Yet, there do occur real differences between the theoretical modeling and experiment. For example, the type of scattering potential invoked in the Durst *et al.* theory differs from the experimental situation, where measurements involve low-disorder, extremely high mobility specimens including mostly small angle scattering.[1,8] In addition, the current domain picture of Andreev *et al.* includes boundary conditions,[9] which appear difficult to realize in the Hall bar type specimen.[31]

A complementary approach,[12] which modeled the specimen as a tunnel junction, also realized magnetoresistance oscillations with a period and phase that were approximately consistent with Ref. 1.[1,12] This theory indicated, in addition, an N-shape current-voltage (*I-V*) characteristic in a regime of radiation-induced negative conductivity, analogous to Andreev *et al.*[9,12] Subsequent theoretical work by Bergeret, Huckestein, and Volkov provided clarification and proposed, in the strong B-field limit, an S-shape *I-V* characteristic for Hall bar devices and an N-shape *I-V* characteristic for the Corbino device,[17] the geometry dependence following from the boundary conditions in the 2DES. These works impressed the idea that *I-V* characteristics of the ZRS, which appear calculable from theory, might serve as an incisive and confirming probe of the underlying physics.

In short, the possible transformation of a predicted negative resistivity/conductivity state, into the vanishing resistance state reported by experiment, in a strong B-field limit where vanishing resistance and vanishing conductance are equivalent, and the associated *I-V* characteristics, appear to be issues in the theoretical discussion.[1,2,6,8–10,12,14,16,17]

In comparison, experiment indicates a ZRS which is approached exponentially versus T, following $R_{xx} \approx \exp(-\Delta/k_B T)$, where Δ is an activation energy.[1,2] By invoking an analogy to QHE, where large amplitude (Shubnikov-de Haas) resistance oscillations show similar ZRS while exhibiting activated transport,[4] such transport behavior has been cited as evidence for a radiation-induced gap in the electronic spectrum.[1]

Shi and Xie have argued that a negative conductance instability could induce a state transition and a new electronic phase, which includes a physical rearrangement of the system.[12,16] It appears that this possibility could also be addressed by comparing experiment with model predictions.[5–30] Thus, we examine the radiation induced vanishing resistance states and associated voltage-current (*V-I*) characteristics in ultra-high-mobility GaAs/AlGaAs heterostructures. In a Hall geometry, we demonstrate that the non-linear *V*-*I* curve at $B=(4/5)B_f$ in the absence of radiation becomes linearized as $R_{xx}\to 0$ under the influence of radiation, to relatively high currents. The power variation of R_{xx} at the minima is also reported and these data suggest that a variable such as $\log(P)$, where P is the radiation power, might play a role that is approximately analogous to the inverse temperature in activation studies. The observed differences between experiment and available model predictions seem to suggest that additional physics might be involved in the ZRS that is observed in the irradiated-2DES.

II. EXPERIMENT

Experiments were carried out on Hall bars, square shaped devices, and Corbino rings, fabricated from GaAs/AlGaAs heterostructures. After a brief illumination by a red LED, 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 $\mu(1.5\text{ K})$ upto $1.5\times 10^{7}\text{ cm}^2/\text{V s}$. Low frequency lock-in based electrical measurements were carried out with the sample mounted inside a waveguide and immersed in pumped liquid He-3, over the *T*-range $0.4\leqslant T\leqslant 3$ K. Lock-in based *V*-*I* measurements were carried out by quasi-statically ramping the excitation voltage in the ac constant-current circuit. Electromagnetic (EM) waves in the microwave part of the spectrum, $27\leqslant f\leqslant 170$ GHz, were generated using various tunable sources. The radiation intensity was set at the source and subsequently reduced using variable attenuators for the reported experiments at 119 GHz, where the power in the vicinity of the sample is estimated to be less than 1 mW. Measurements at 50 GHz were carried out using a signal generator with calibrated output power.[32] Thus, the source output power at 50 GHz is given in absolute units.

III. RESULTS

Figure 1 shows the magnetoresistance measured with (w/) and without (w/o) electromagnetic wave excitation for $B\leqslant 0.34$ T. This specimen satisfies the strong field condition, $\omega_c\tau>1$, for $B>1$ mT. Here ω_c is the cyclotron frequency and τ is the transport relaxation time. Figure 1(a) indicates SdH oscillations, which are visible down to $B\approx 0.1$ T at 0.7 K, in the absence of radiation. The application of radiation induces oscillations,[33–36] and reduces the resistance over finite *B*-intervals in the vicinity of $B=[4/(4j+1)]B_f$, where $B_f=2\pi f m^*/e$,[1,33,36] m^* is the effective mass,[37] e is the charge of the electron, and $j=1,2,3,\ldots$. Indeed, ZRS are visible over broad *B*-intervals in the vicinity of $(4/5)B_f$ and $(4/9)B_f$, as the SdH oscillations are suppressed about the ZRS by the radiation.[1,38–42]

In Fig. 1(b), the data of Fig. 1(a) have been plotted as a function of the normalized inverse magnetic field, where the normalization factor, δ, is the period in B^{-1} of the radiation-induced resistance oscillations.[1] Figure 1(b) indicates that the photoexcited (w/radiation) data cross the dark (w/o radiation) data at integral and half-integral values of the B^{-1}/δ, when $B^{-1}/\delta\geqslant 2$ (see also Fig. 3 of Ref. 1). At these B^{-1}/δ, the photon energy hf spans an integral, j, or half integral, $j+1/2$, cyclotron energies. The crossing feature in the vicinity of integral B^{-1}/δ appears to be in agreement with the theoretical prediction.[8,12] Shi and Xie have suggested that, when $2\pi f/\omega_c=j$, the conductivity in the presence of radiation, σ, equals the conductivity in the absence of radiation, σ_{dark}, i.e., $\sigma=\sigma_{dark}$.[12] Remarkably, the data suggest the same behavior at $j+1/2$. The data of Fig. 1(b) also show that resistance minima occur about $j+1/4$, while higher order resistance maxima occur about $j+3/4$. Experiment suggests that the resistance maxima generally obey this rule for integral j, excepting $j=0$, where phase distortion associated with

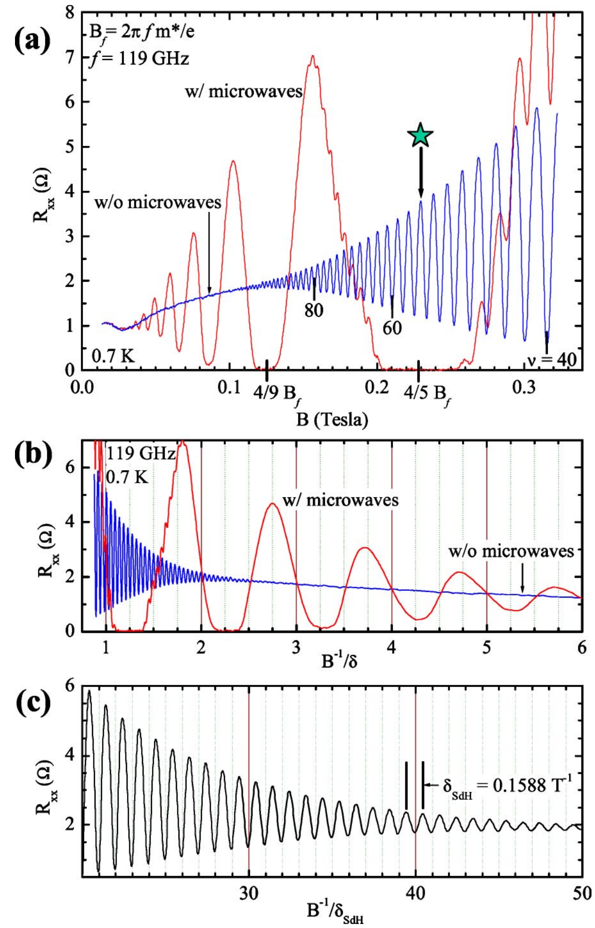

FIG. 1. (Color online) (a) The magnetoresistance R_{xx} in a GaAs/AlGaAs heterostructure device with (w/) and without (w/o) microwave excitation at 119 GHz. Without radiation, Shubnikov-de Haas (SdH) oscillations are observable in the resistance about $(4/5)B_f$. Radiation reduces the resistance R_{xx} and eliminates the SdH oscillations in the vicinity of $(4/5)B_f$ and $(4/9)B_f$. The star marks the *B*-field at which V_{xx} vs I measurements are reported (see Fig. 2). (b) A plot of the resistance data of (a) versus the normalized inverse magnetic field demonstrates periodicity, with period δ, of the radiation induced oscillations in B^{-1}/δ. The curves with- and without-radiation intersect in the vicinity of integral and half-integral values of the abscissa. (c) A plot of the dark (w/o radiation) R_{xx} data of (a) versus $B^{-1}/\delta_{\mathrm{SdH}}$ helps to determine the phase of the Shubnikov-de Haas oscillations. Here, δ_{SdH} is the period of the SdH oscillations. Note that SdH resistance minima occur at integral values of $B^{-1}/\delta_{\mathrm{SdH}}$, suggesting that R_{xx} is proportional to $-\cos(2\pi F_{\mathrm{SdH}}/B)$, where $F_{\mathrm{SdH}}=\delta_{\mathrm{SdH}}^{-1}$.

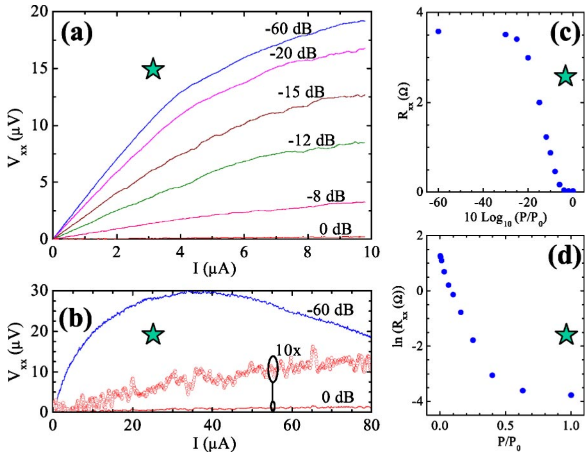

FIG. 2. (Color online) (a) The diagonal voltage (V_{xx}) is shown as a function of the current (I) for a number of radiation intensities. The measurements were carried out at the B-field that is identified by a star in Fig. 1(a). At (−60 dB), there is a sub-linear increase of V_{xx} vs I above 4 μA. Increasing the radiation intensity, i.e., tuning the attenuation factor toward 0 dB, reduces the slope and linearizes the V_{xx} vs I curve. (b) The diagonal voltage V_{xx} is shown as a function of I to $I=80$ μA, with (0 dB) and without (−60 dB) microwave excitation. Within experimental resolution, the V_{xx} vs I curve with excitation appears mostly linear to 80 μA. (c) R_{xx} evaluated from the initial slope of the V_{xx} vs I curves of (a) are plotted as a function of the power attenuation factor. Here, P is the attenuated radiation intensity, and P_0 is the source intensity. (d) The natural logarithm of R_{xx} is plotted vs P/P_0.

the last peak seems to shift it from the $2\pi f/\omega_c = 3/4$ to approximately 0.85(±0.03) (see Fig. 3(a)).

In order to compare the relative phases of radiation-induced resistance oscillations and the SdH effect, SdH oscillations have been shown in a normalized B^{-1} plot in Fig. 1(c), where the normalization factor δ_{SdH} is the SdH period in B^{-1}. In Fig. 1(c), the resistance minima of SdH oscillations appear at integral values $(j=1,2,3,\ldots)$ of the abscissa $B^{-1}/\delta_{\mathrm{SdH}}$,[43] implying oscillations of the form $R_{xx} \approx -\cos(2\pi F_{\mathrm{SdH}}/B)$, where $F_{\mathrm{SdH}} = \delta_{\mathrm{SdH}}^{-1}$. Thus, there appears to be a phase difference between the observed oscillations $(-\cos(2\pi F_{\mathrm{SdH}}/B))$ and the assumed form for the density-of-states (DOS) $(+\cos(2\pi\varepsilon/\omega_c))$ of Ref. 8, which is attributed here to the suppression of the zero-point energy shift, $\hbar\omega_c/2$, by theory.[8] If this physically manifested constant energy shift $\hbar\omega_c/2$ is included in ε, then the DOS at low-B looks like $\eta(\varepsilon) = \eta_0 - \eta_1(\cos(2\pi\varepsilon/\hbar\omega_c))$, with η_1 positive. Unlike SdH oscillations, the radiation induced oscillations exhibit minima for B^{-1}/δ about $j+1/4$ (see Fig. 1(b)).

Results of V-I studies in the vicinity of the $(4/5)B_f$ resistance minimum, at the B-value marked by the star in Fig. 1(a), are summarized in Fig. 2. Fig. 2(a) shows V_{xx} vs I to $I=10$ μA for several power attenuation factors. In the absence of radiation (−60 dB), V_{xx} vs I is initially ohmic at low currents ($\leqslant 3$ μA), before non-linearity, possibly due to heating, becomes apparent above 4 μA. The application of radiation leads to a progressive reduction in the initial slope of the V_{xx} vs I curves, signifying a decrease in R_{xx} in the vicinity of $(4/5)B_f$ under photoexcitation. The data suggest, in addition, that the onset of non-linearity shifts to higher current with increasing radiation intensity. This feature implies that the initial linear region observed in the absence of radiation is extended to higher currents under the influence of radiation. If the observed non-linearity originates from heating, then its shift to higher currents under radiation implies also that heating effects are reduced under photoexcitation, over the resistance minima.

Experimental results to higher currents shown in Fig. 2(b) confirm the features observed in Fig. 2(a). Here, the data indicate a negative differential resistance $r_{xx} = dV_{xx}/dI < 0$ above $I=40$ μA in the absence of radiation (−60 dB), while $r_{xx} > 0$ with microwave excitation (0 dB) for the entire range of currents. Notably, non-linearity in the V-I curve under radiation, if any, appears only above 50 μA, although the Hall voltage $V_{xy}(10\ \mu\mathrm{A}) = 4.69$ mV exceeds the Landau level spacing $\hbar\omega_c/e \approx 0.39$ mV by nearly an order of magnitude even at $I=10$ μA, i.e., $V_{xy}(10\ \mu\mathrm{A}) \gg \hbar\omega_c/e$.

An investigation of the resistance in a Corbino geometry specimen at $B=(4/5)B_f$ and $B=(4/9)B_f$ under microwave excitation also showed current-independent characteristics over the investigated range, similar to what has been shown for a Hall geometry in Fig. 3 of Ref. 1. In the Corbino configuration, a maximum in the resistance (or a minimum in the conductance) was observed at $B=(4/5)B_f$ and $B=(4/9)B_f$, supplementing the usual result for the Hall configuration. The difference was attributed to the well-known feature of transport, that the Corbino resistance $R_C \approx \sigma_{xx}^{-1}$ while the diagonal resistance in a Hall geometry $R_{xx} \approx \sigma_{xx}/\sigma_{xy}^2$ under the $\omega_c\tau > 1$ condition. Here, σ_{xx} and σ_{xy} are the diagonal and off-diagonal components of the conductivity tensor.

The observed change in the V-I characteristics with the radiation intensity in Fig. 2(a) appears, as mentioned before, closely correlated to the radiation-induced modification of the diagonal resistance at the resistance minima. Experiments show that, at a constant temperature, the resistance minima become deeper with increasing radiation intensity, until the onset of "breakdown."[1,40] On the other hand, at constant radiation intensity, the resistance shows activated transport characteristics as a function of the temperature.[1,2] Thus, intuitively, it appears that reducing the temperature and increasing the radiation intensity play a similar role in the phenomenology. But the connections are not well understood and, therefore, the effect of radiation at the deepest resistance minima is further examined here. The effect of radiation intensity at the higher order R_{xx} minima have been reported elsewhere.[38]

Thus, R_{xx} evaluated from the initial slope of the V-I data of Fig. 2(a) have been shown in Fig. 2(c) as a function of $10\log_{10}(P/P_0)$, where P_0 is the (constant) output power of the radiation source, and P is the attenuated power. This data plot shows a constant resistance between −60 and −30 dB, followed by a rapid decrease at higher power levels (>−30 dB); the resistance becomes small on the exhibited scale above −5 dB. Figure 2(d) shows an alternate plot with the natural logarithm of the resistance on the ordinate versus the normalized power on a linear scale along the abscissa. This figure suggests that, for $P/P_0 < 0.3$, $R_{xx} \approx \exp[-a(P/P_0)]$, with $a \approx 12$.

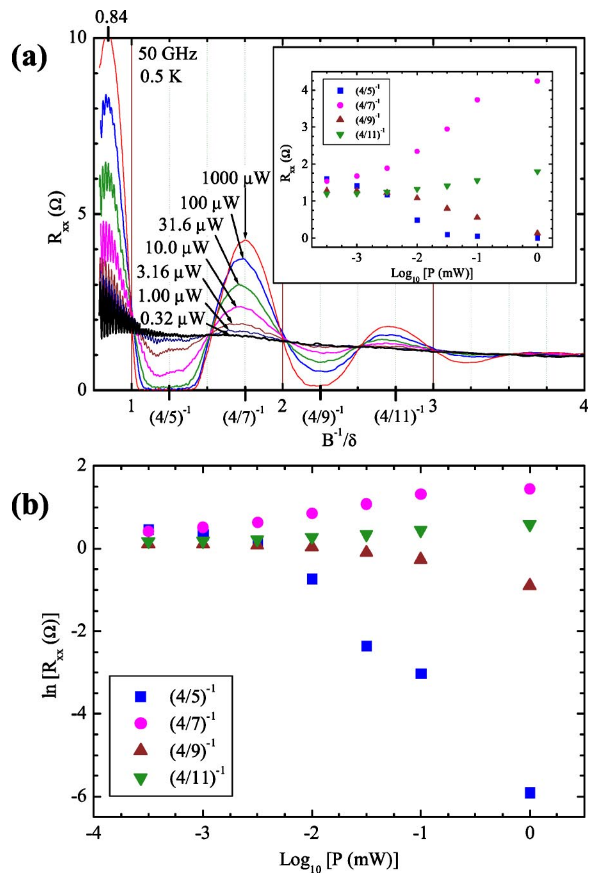

FIG. 3. (Color online) (a) Radiation induced resistance oscillations at $f=50$ GHz are exhibited for a number of source intensities, in units of μW. The inset shows the extrema resistance at $(4/5)^{-1}$, $(4/7)^{-1}$, $(4/9)^{-1}$, $(4/11)^{-1}$ vs the logarithm of the power. (b) The logarithm of the extrema resistance vs the logarithm of the power. A comparison with typical activation plots (e.g., see Fig. 3(d) of Ref. 1) suggests that, on the resistance minima, $\log(P)$ might be analogous to T^{-1}.

Further measurements addressing this issue are illustrated in Fig. 3. Here, vanishing resistance is observable with a source power of 100 μW about $B^{-1}/\delta=(4/5)^{-1}$. Other features such as resistance minima near $[4/(4j+1)]^{-1}$, resistance maxima near $[4/(4j+3)]^{-1}$ for $j>1$, nodes in the resistance in the vicinity of j and $(j+1/2)$, and the intersection of the data curves obtained at different powers in the vicinity of the nodes, are consistent with the results shown for $f=119$ GHz in Fig. 1(b). Note also that the first resistance maximum occurs in the vicinity of $B^{-1}/\delta\approx 0.84$. That is, this resistance maximum occurs slightly below $B^{-1}/\delta=1$, implying a magnetic field for this feature that is slightly above B_f. The power dependence of the resistance at the $(4/5)^{-1}$ and $(4/9)^{-1}$ minima, and the $(4/7)^{-1}$ and $(4/11)^{-1}$ maxima are shown in the inset of Fig. 3(a) and in Fig. 3(b). In Fig. 3(b), the ordinate shows $\ln(R_{xx})$, while the abscissa shows $\log_{10}(P)$. Remarkably, the plot shown in Fig. 3(b) looks very similar to the activation plots,[1,2] which suggests that the logarithm of the radiation power might play a role in power dependent studies that is analogous to the inverse temperature in activation studies, at least at the $(4/5)^{-1}$ and $(4/9)^{-1}$ minima.

IV. DISCUSSION

The voltage-current characteristics in the regime of the radiation induced zero-resistance states could serve to provide valuable understanding into the physical mechanism underlying the phenomenon since such characteristics can be measured through experiment and, at the same time, they appear calculable from existing theory,[12,14,17] which facilitates a comparison between experiment and theory.

At the present, it is believed that there ought to be either a threshold electric field for the onset of current in a Corbino geometry or a threshold current density for the onset of dissipation in a Hall geometry.[17] Thus, the naive expectation has been that a linear voltage-current characteristic in the absence of radiation should be transformed into a non-linear characteristic under the influence of radiation.

Theoretical expectations for a non-linear voltage-current characteristic under photoexcitation are motivated as follows: As the amplitude of the radiation induced resistivity/conductivity oscillations increases with increasing radiation intensity, the oscillatory minima approach and then, in principle, cross over into a negative conductivity/resistivity regime.[6,8,10,12] However, the physical instability of negative resistivity/conductivity prevents the actual observation of negative resistance/conductance. It leads instead to a locking of the measured resistance/conductance at zero-resistance/conductance, along with a stratification of current into two oppositely directed current domains.[9] As these current domains are thought to be characterized by an unspecified current density j_0, the domains are expected to rearrange themselves and carry an applied current in a Hall device without dissipation, so long as the current density associated with the applied current does not exceed approximately $j_0/2$. Thus, vanishing V_{xx} should be observed below some critical applied current in a Hall geometry. Above the critical current, however, there should then be a tendency to destroy the zero-resistance state as the domains are unable to accommodate the applied current, and a non-linear voltage-current characteristic is supposed to reveal such a breakdown of the radiation induced zero-resistance states with increasing current.

The experimental results for the Hall geometry shown in Fig. 2 appear, however, quite unlike expectations: The voltage-current characteristic is non-linear in the absence of radiation and it becomes linearized under the application of radiation. Here, an unexpected result seems to be the non-linearity and the negative differential resistance in the absence of radiation in the high mobility specimen, and the suppression of this non-linearity by the radiation.

An important supplementary feature of experiment is that, at the oscillatory resistance minima, there is an activated-type temperature dependence of the resistance.[1,2] The results reported here seem to suggest that, in addition to the activated temperature dependence at the minima, the voltage-current characteristics constitute yet another thought-provoking problem in this field. The reported voltage-current characteristics, when coupled with the activated temperature resistance at the minima, seem to leave open the possibility that the observed zero-resistance states might be a consequence of a vanishing bulk diagonal resistivity, similar to the quantum Hall situation. That is, it could be that the diagonal resistance saturates at zero-resistance in activated fashion under photo-excitation because the diagonal resistivity approaches zero-resistivity in a similar way. Further experiments seem necessary, however, to clarify this point.

V. SUMMARY

In summary, we have examined the voltage-current characteristics and the role of the microwave power in the novel radiation induced zero-resistance states in the high mobility 2DES. The *V-I* measurement suggests a linearization of the device characteristics with the application of radiation, while the power dependence at the minima suggests that the logarithm of the radiation intensity might play a role that is similar to the inverse temperature in activation studies. To our knowledge, these features have not been predicted by theory and, therefore, they seem to provide further motivation for the study of this remarkable new effect.[3]

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