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B-periodic oscillations in the Hall-resistance induced by a dc-current-bias under combined microwave-excitation and dc-current bias in the GaAs/AlGaAs 2D system

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We report the observation of dc-current-bias-induced *B*-periodic Hall resistance oscillations and Hall plateaus in the GaAs/AlGaAs 2D system under combined microwave radiation- and dc bias excitation at liquid helium temperatures. The Hall resistance oscillations and plateaus appear together with concomitant oscillations also in the diagonal magnetoresistance. The periods of Hall and diagonal resistance oscillations are nearly identical, and source power (*P*) dependent measurements demonstrate sub-linear relationship of the oscillation amplitude with *P* over the span $0 < P \leq 20\,\text{mW}$.

Magnetotransport studies of two-dimensional electron systems (2DES) subjected to microwave, mm-wave, and terahertz photoexcitation have revealed many interesting phenomena including the radiation-induced zero-resistance states and associated radiation-induced magnetoresistance oscillations, which have drawn attention from both experiment and theory[1–48]. It is by now well-known that the above mentioned radiation-induced magnetotransport effect consists of 1/4-cycle phase-shifted $1/B$-periodic oscillations, where the oscillatory minima emerge in the vicinity of $B = [4/(4j+1)]B_f$, where $B_f = 2\pi f m^*/e$, f is the microwave frequency, m^* is the effective electron mass and $j = 1, 2, 3\ldots$. Such oscillatory magnetoresistance is mostly observed, at modest radiation-intensity, in the regime of approximately $2\pi f > \omega_c$, where ω_c is the cyclotron frequency. It turns out that, in addition to the above mentioned $1/B$ periodic photo-excited magnetotransport effects, there are also B-periodic oscillatory photo-excited magneto-oscillations in both the diagonal resistance, R_{xx}, and the photo-voltage V_p. In contrast to $1/B$ periodic photo-excited magnetotransport effects which occur approximately when $2\pi f > \omega_c$, these B-periodic magneto-oscillations in the R_{xx} and V_p are typically observed at $2\pi f < \omega_c$, i.e., $B > B_f$[49–52] Further, initial reports[49,50] proposed that the oscillation period, ΔB, follows $\Delta B \propto n_e/\omega L$, where n_e is electron density and L is the distance between potential probes along the Hall bar. Such oscillations in R_{xx} and V_p were attributed to the interference of coherently excited edge magnetoplasmons (EMP) at contacts along the periphery of the sample[49,50,53,54]. In their study, Stone *et al.*[52] confirmed the existence of such B-periodic oscillations in the regime $2\pi f < \omega_c$, in specimens where both the $1/B$ periodic and the B periodic photo-excited magneto oscillations occur together. However, they found that the period ΔB is independent of L, the spacing between adjacent contacts[52], which suggested a reduced role for the interference between edge magnetoplasmons excited at adjacent contacts, and generally pointed to effects within a contact.

Here, we report the observation of B-periodic oscillations, ΔR_{xy}, in the Hall resistance, R_{xy}, which go together, remarkably, with plateau-like features in the Hall resistance trace, and examine the correlation of these ΔR_{xy} oscillations with B-periodic diagonal magnetoresistance oscillations, ΔR_{xx}, induced by microwave photo-excitation. Critically, it turns out that the realization of such B-periodic oscillations in both R_{xy} and R_{xx} in our specimens requires the injection of a supplemental dc-current, I_{dc}, into the specimen. The observed B-periodic oscillations in ΔR_{xy} and ΔR_{xx} appear very similar, although the ΔR_{xy} oscillations are larger in magnitude, their amplitudes increase sub-linearly with the microwave power, and the period ΔB decreases with increasing microwave

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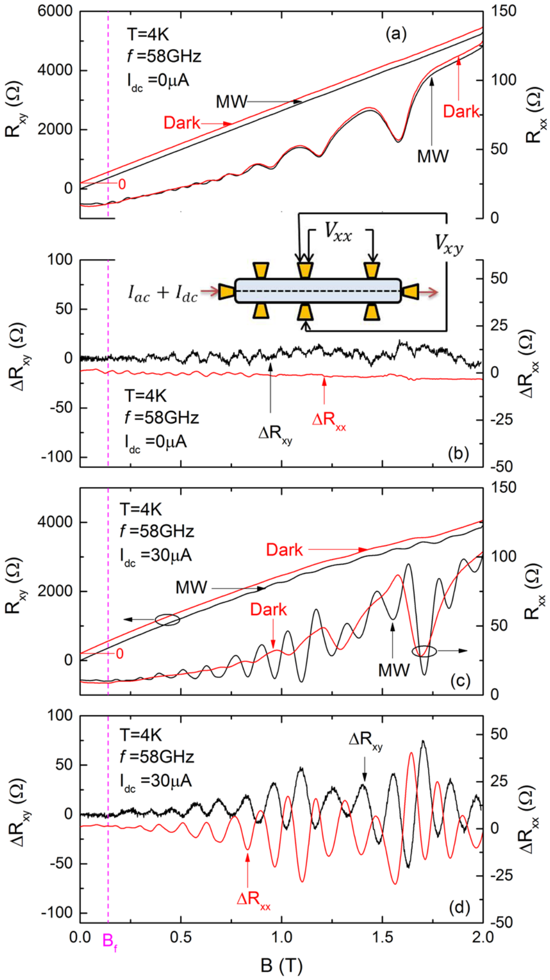

Figure 1. The inset shows a schematic of the sample and the measurement configuration. (**a**) The Hall resistance, R_{xy}, and diagonal resistance, R_{xx}, measured under both dark- and photo-excited ($f = 58\,GHz$) conditions with $I_{dc} = 0\,\mu A$. The dark R_{xy} has been offset with respect to the photo-excited curve for the sake of clarity. The characteristic field of cyclotron resonance, labeled as B_f, is indicated by the dashed vertical line. (**b**) This panel shows the difference between the photo-excited and dark resistances shown in Fig. 1(a), i.e., $\Delta R_{xy} = R_{xy}^{(photo-excited)} - R_{xy}^{(dark)}$, and $\Delta R_{xx} = R_{xx}^{(photo-excited)} - R_{xx}^{(dark)}$. (**c**) The Hall resistance, R_{xy}, and diagonal resistance, R_{xx}, measured under both dark- and photo-excited ($f = 58\,GHz$) conditions with a supplemental $I_{dc} = 30\,\mu A$. Upon applying $I_{dc} = 30\,\mu A$, the photo-excited R_{xy} starts exhibiting B-periodic oscillations at high B. Concurrently, B-periodic oscillations appear on the SdH oscillations in R_{xx}. (**d**) ΔR_{xy} (left ordinate) and ΔR_{xx} (right ordinate) obtained from the data of Fig. 1(c) are plotted vs. B. The results suggest anti-phase B-perioidic oscillations in ΔR_{xy} and ΔR_{xx}.

frequency, *f*. The necessity of a supplemental *dc*-current for the observability of this effect suggests a role for heating in this observed 2DES effect.

Results

Figure 1(a) shows the dark and photo-excited R_{xy} (left ordinate) and R_{xx} (right ordinate) vs. the magnetic field B to $B = 2$ Tesla. Here, the supplemental dc-current bias, $I_{dc} = 0$, and the frequency of microwave excitation for the photo-excited trace is $f = 58\,GHz$. Note that the dark R_{xy} has been offset with respect to the photo excited R_{xy} trace for the sake of clarity. The Fig. 1(a) shows that the dark and photo-excited traces are nearly the same. Indeeed, subtracting the photo-excited data from the dark data for both R_{xy} and R_{xx} shows a vanishing residual. These residuals shown as $\Delta R_{xy} = R_{xy}^{(photo-excited)} - R_{xy}^{(dark)}$ and $\Delta R_{xx} = R_{xx}^{(photo-excited)} - R_{xx}^{(dark)}$ in Fig. 1(b) are vanishingly small in comparison to the as-collected signals. Thus, at first sight it looks like there is hardly a difference between the photo-excited and dark curves in the absence of a *dc*-current bias, although a close examination shows small Shubnikov-de Haas (SdH) in the residue since the SdH oscillations are slightly suppressed by the microwaves. The characteristic field for cyclotron resonance is labeled as $B_f = 2\pi f m^*/e$, where f is microwave frequency, m^* is effective mass, e is the electron charge, and it is indicated by the dotted vertical line. Figure 1(c,d) show the transport results when a supplemental *dc*-current bias is applied to the sample. Here, when $I_{dc} = 30\,\mu A$, the photo-excited R_{xy} shows evidence for Hall oscillations with plateau like features in comparison to dark R_{xy} for $B \geq 0.5$ Tesla, see

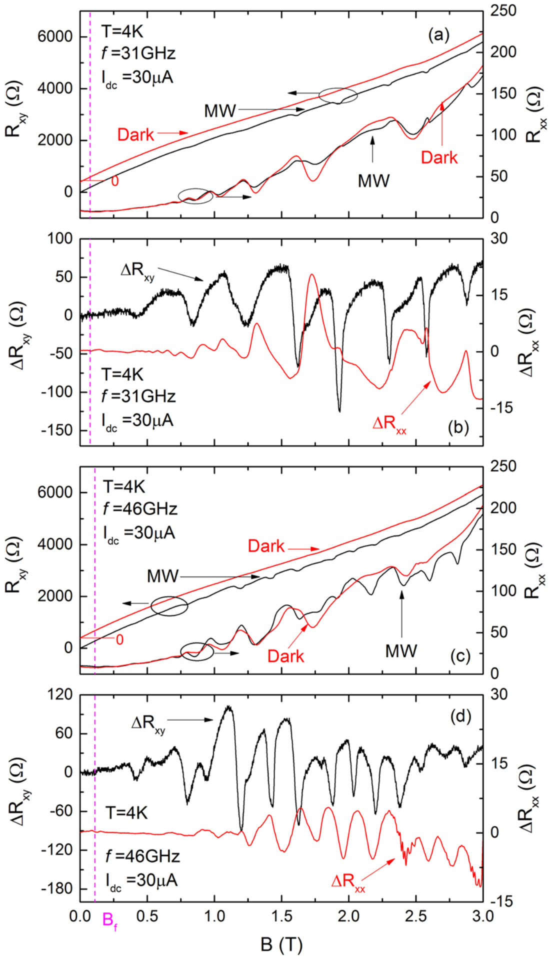

Figure 2. The photo-excited- and dark- curves of R_{xy} and R_{xx} at $I_{dc} = 30\,\mu A$, and (**a**) $f = 31$ and (**c**) $f = 46\,GHz$. Panel (b) and (d) show ΔR_{xy} and ΔR_{xx} at $f = 31$ and $46\,GHz$ respectively. Note the variation of the period of the B-periodic oscillations with f.

Fig. 1(c). Again, the dark R_{xy} has been offset with respect to the photo-excited R_{xy} for the sake of clarity. Concurrently, the R_{xx} trace shows strong B-periodic oscillations on top of the SdH oscillations, which were evident in R_{xx} of Fig. 1(a). [Such behavior is also observable in Fig. 2(a,d), which also suggest some harmonic distortion in the SdH oscillations under these experimental conditions]. The background subtracted ΔR_{xy} and ΔR_{xx} extracted from Fig. 1(c) have been plotted in Fig. 1(d). This figure demonstrates strong B-periodic oscillations in both R_{xy} and R_{xx} induced by the application of the I_{dc} in the presence of microwave photo-excitation for $B > 0.25$ Tesla. The maxima (minima) of ΔR_{xy} oscillations align with the minima (maxima) of ΔR_{xx} oscillations. An observable beat in the B-periodic oscillations, which did not show an obvious dependence on f, occurs for $B \approx 1.3$ Tesla. This feature suggests the possibility of interference between two harmonic terms closely spaced frequency, and differing in frequency by $\leq 10\%$. Note that ΔR_{xy} and ΔR_{xx} oscillations are observed for $B > B_f$.

Similar results are shown in Fig. 2 at other f. Figure 2(a,c) exhibit photo-excited and dark R_{xy} and R_{xx} curves at $I_{dc} = 30\,\mu A$ and $f = 31$ and $46\,GHz$ respectively. As in Fig. 1(c), additional small B-periodic oscillations become evident on the R_{xy} and R_{xx} under the combined application of both the current bias and the microwave photo-excitation. The additional B-periodic features on the photo-excited R_{xy} in Fig. 2(a,c) have a distinct plateau-like appearance to them. Figure 2(b,d) show ΔR_{xy} and ΔR_{xx} at $f = 31$ and $46\,GHz$ respectively. In both Fig. 2(b,d), B-periodic oscillations appear in ΔR_{xy} and ΔR_{xx} above B_f. Note that the period of the these microwave- and current-bias-induced oscillations decreases with increasing microwave frequency.

Figure 3 examines the microwave source power, P, dependence of ΔR_{xy}, in panel (a), and ΔR_{xx}, in panel (b), vs. B at $f = 58\,GHz$. From Fig. 3(a,b), it is apparent that both ΔR_{xy} and ΔR_{xx} oscillation amplitudes are enhanced by increasing P. A closer investigation suggests that the B positions of oscillatory extrema move toward high B as P increases. Panel (c) and (d) exhibit the amplitudes of specified oscillatory maximum (labeled with an asterisk) of ΔR_{xy} and ΔR_{xx} as a function of P at $f = 58\,GHz$. The data illustrate a sub-linear relation between the amplitude and P. A power law function, $\Delta R \propto P^{\alpha}$, has been applied to the experimental data to extract α characterizing the increase in the amplitude with P. The preliminary results indicate that $\alpha \approx 0.55 \pm 0.1$, which suggests that the oscillation amplitude could be sensitive to the magnitude of the microwave electric field, E, since $E \propto P^{0.5}$[19].

To determine the periodicity of the B-periodic oscillations, the oscillatory maxima of R_{xy} and R_{xx} were assigned to integer values and the oscillatory minima to half-integer values. The plots of the oscillation index, N

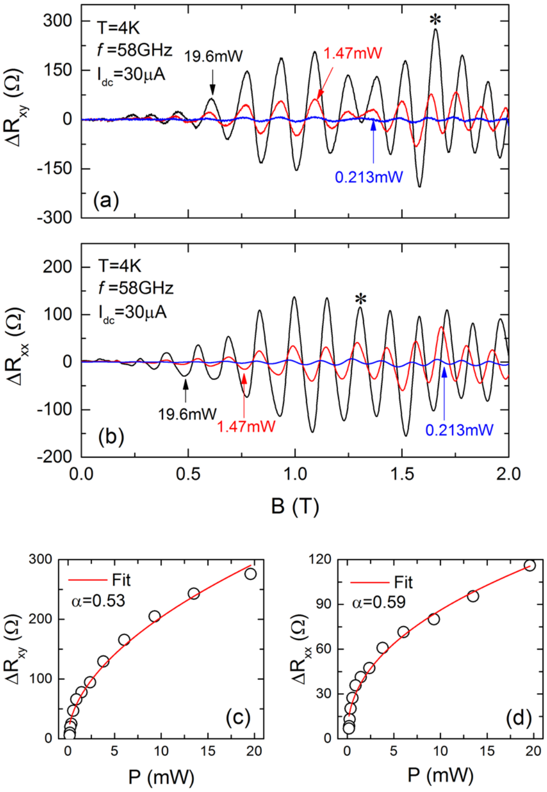

Figure 3. The microwave source-power P dependence data for (**a**) ΔR_{xy} and (**b**) ΔR_{xx} vs. B at $I_{dc} = 30\,\mu A$ and $f = 58\,GHz$ suggests that the amplitude of oscillations increases with increasing P. At the same time, there is a slight shift in the B positions of oscillatory extrema with increasing P. The amplitudes of oscillatory maxima (labeled with an asterisk) of (**c**) ΔR_{xy} and (**d**) ΔR_{xx} as a function of P suggests a non-linear increase in the amplitude with P. The function, $\Delta R \propto P^{\alpha}$, serves to fit the experimental data. The extracted α, indicated in Fig. 3(c,d) confirm a sub-linear relationship between amplitude and P for both ΔR_{xy} and ΔR_{xx} oscillations.

as a function of the extremal B-value for the oscillatory R_{xy} and R_{xx} for $f = 31$, 40, 46, and 58 GHz are exhibited in Fig. 4(a,b); these plots confirm a linear relationship indicating that the R_{xy} and R_{xx} oscillations are periodic-in-B. The period, ΔB, of the R_{xy} and R_{xx} oscillations as a function of f are plotted in Fig. 4(c), while the inset shows a plot of $1/\Delta B$ vs. f. Since data points are shown at only four frequencies in Fig. 4(c), it is difficult to clarify the functional dependence of the oscillatory effect on the microwave frequency from these measurements. Studies at higher frequencies appear necessary to further investigate the relationship between the period of oscillations and microwave frequency.

Discussion

Plasmons are collective excitations of electronic system that arise upon displacing electrons from their equilibrium positions with respect to the background positive charge[54]. A GaAs/AlGaAs 2DES is expected to exhibit a collective plasmon response in the absence of a magnetic field, i.e., $B = 0$, following the dispersion $\omega_p^2 = ne^2k/2\varepsilon_{eff}\varepsilon_0 m^*$, where ω_p is the plasmon frequency, n is the electron density, e is the electron charge, k is the plasmon wave vector, m^* is the effective mass, and for the GaAs/AlGaAs 2DES, $\varepsilon_{eff} = (\varepsilon_{GaAs} + \varepsilon_{vac})/2$, with $\varepsilon_{GaAs} = 12.8$, and $\varepsilon_{vac} = 1$[55]. The application of a transverse magnetic field leads to a hybridization of cyclotron resonance with this plasmon, producing the (bulk) magnetoplasmon which follows $\omega_{mp}^2 = \omega_p^2 + \omega_C^2$[54]. In a strip or Hall bar geometry, the length scale established by the boundary helps to determine the quantization condition or allowed values for the plasmon wavevector, k. Vasiliadou *et al.* investigated the transport signature of this phenomenon in Hall bars and found that their data could be described by $k = \pi/W$, where W is the width of the device[55]. This suggests that the finite sized specimen should exhibit the magnetoplasmon or plasmon shifted cyclotron resonance ($hf = \hbar\omega_{mp}$) in place of the bare cyclotron resonance ($hf = \hbar\omega_C$). In addition to the lowest mode, it is possible to also have additional allowed plasmon modes at wave vectors k, i.e., $k = n\pi/W$, with $n = 2, 3, 4\ldots$. Then, one expects additional magnetoplasmon branches to also leave behind a signature in transport. However, all these magnetoplasmon resonances would be expected to occur at magnetic fields below the bare cyclotron resonance magnetic field at a fixed frequency, f, for photoexcitation, i.e., $B \le B_f = 2\pi f m^*/e$.

In addition to bulk plasmons, there exist edge plasmons that occur in bounded specimens. In contrast to the bulk plasmons, the mode frequencies of edge magnetoplasmons decrease with increasing magnetic field and follow the relation $\omega_{emp} = ((2^{1/2}/3)(3\omega_p^2 + \omega_C^2)^{1/2} - \omega_c) \sim \omega_p^2/\omega_c$[54]. As with bulk magnetoplasmons, many edge magnetoplasmon modes are possible, one for each allowed value for k in the bounded specimen

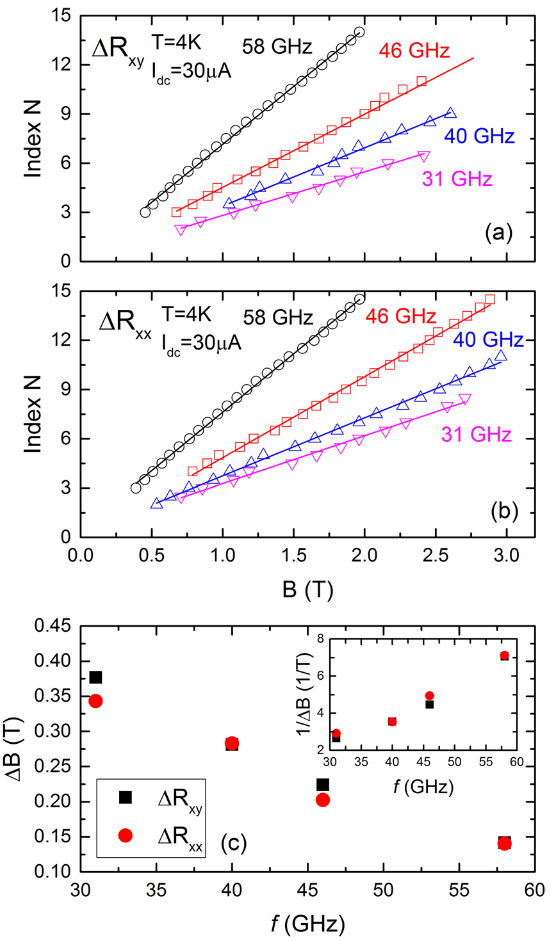

Figure 4. This figure shows plots of the extremal index vs. B, for both the ΔR_{xy} (panel (a)) and the ΔR_{xx} (panel (b)). Here, oscillatory maxima have been assigned with integer values while minima have been assigned half integer values. These half-cycle plots have been shown for $f = 31$, 40, 46, and 58 *GHz*. Note the straight line fits through the data. The results confirm B-periodicity in the I_{dc} induced magneto-oscillations. (**c**) This panel shows plots of ΔB vs. f and, in the inset, $1/\Delta B$ vs. f extracted from Fig. 4(a,b).

As mentioned, our study reveals strong B-periodic oscillations in the Hall resistance that go together with the R_{xx} oscillations. Remarkably, the features in the R_{xy} trace even have a plateau like appearance associated with them, see Fig. 2(a,c). Such B-periodic oscillations in the Hall resistance have not been reported before, to our knowledge. On the other hand, the B- periodic oscillations in R_{xx} appearing in this study under microwave excitations are similar to the B-periodic oscillations in R_{xx} discussed in ref.[49]. Further, in our study, it appears vitally important to apply a supplementary current, i.e., a dc-current bias, to realize the B-periodic oscillations. It is the moderate microwave excitation in the presence of the dc-current bias that helps to bring out the B-periodic oscillations in both R_{xy} and R_{xx}. Although such data from our study have not been shown here, the period of observed B-periodic oscillations in the R_{xx} did not depend on the spacing of the voltage contacts, as in the work of Stone *et al.*[52]. Early work claimed an edge magnetoplasmon origin for such B-periodic R_{xx} oscillations based on the dependence of the period on microwave frequency, electron density, and distance between potential contacts. As mentioned, such oscillations were attributed to the interference of coherently excited edge magnetoplasmons (EMP) at adjacent diagonal voltage contacts along the periphery of the sample[49,50,53]. Yet, the independence of the period on the potential probe distance[52] seems to be, at first sight, in variance with expectations based on the edge magnetoplasmon model. ref.[52] suggested, however, that, given the long decay length of edge magnetoplasmon modes, such can propagate along the whole edge around the sample as a consequence of the high- sample mobility. We note that even in the high mobility sample, thermal dissipation at the source and drain contacts may not support the propagation of edge magnetoplasmons across current contacts. That is, the EMP's on opposite edges of the sample, on either side of the line connecting the source and the drain, are most likely decoupled. In this situation, it is difficult to understand the observed similarity between the magnetooscillations in the R_{xx} and R_{xy} in our measurements since the R_{xy} contacts lie on opposite edges while the R_{xx} contacts lie on the same edge. The requirement of a *dc*-bias for the observability of the effect, together with the improved observability of the effect at higher bath temperatures, $T \approx 4$ K, suggests that the *dc*-bias serves to heat the electron system, and the current heating helps to bring about the obervability of the effect. Certainly, the observed effects are fascinating and further measurements are being carried out to understand their origin, and the role of the *dc*-bias in the electronic system[30,31].

In summary, we have observed a *dc* current bias induced B - periodic Hall-oscillations that go together with longitudinal magnetoresistance oscillations in the GaAs/AlGaAs 2D electron systems under combined microwave- and *dc* bias- excitation. As noted, these B-periodic oscillations in R_{xy} go together with remarkable plateau-like features in the Hall resistance trace. The Hall and longitudinal magnetoresistance oscillations reveal similar period at given microwave frequency as their amplitude increases sub-linearly with the microwave power. The dependence of the observed effect to the *dc*– bias current offers a new method to study the B-periodic magnetooscillations with an easily controlled experimental parameter in a given specimen.

Methods

Sample Preparation. GaAs/AlGaAs heterojunctions were grown by molecular beam epitaxy and 200-μm-wide Hall bars were fabricated by optical lithography, and they included alloyed gold-germanium contacts. The specimen's carrier density and mobility were $n_e \approx 2.4 \times 10^{11}\, cm^{-2}$ and $\mu \approx 11.6 \times 10^6\, cm^2 \cdot V^{-1} \cdot s^{-1}$ at $1.5\,K$ respectively.

Measurement Configuration

A Hall bar was mounted at the end of a $0.5''$-diameter stainless steel waveguide sample holder. The sample holder was immersed into pumped liquid helium. The temperature of the sample was controlled over the span $1.5 \le T \le 4\,K$ by controlling the helium vapor pressure. The magnetic field, produced by a superconducting solenoid, was aligned along waveguide axis and perpendicularly to the sample. Microwaves were generated by a synthesizer over the frequency range $30 \le f \le 50\,GHz$ at a source power $0.1 \le P \le 10\,mW$ and a millimeter wave IMPATT diode source at $f = 58\,GHz$ with a maximal source power 20 mW. The TE_{10} mode microwaves excited by a probe-coupled antenna launcher was transported through the waveguide onto the sample and the electric field was oriented along the Hall bar long axis. The Hall voltage, V_{xy}, and diagonal voltage, V_{xx}, were collected using a four-terminal lock-in technique with an low-frequency *ac* current, I_{ac}, flowing along the Hall bar; as indicated in Fig. 1 inset. A supplemental *dc* current, I_{dc}, was applied along with I_{ac} for a portion of the measurements.

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Author Contributions

Measurements were carried out by H.-C.L. Experimental development and manuscript by H.-C.L. and R.G.M. High quality GaAs/AlGaAs wafers are due to C.R. and W.W.

Additional Information

Competing Interests: The authors declare no competing interests.