APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 14 1 OCTOBER 2001

Giant microwave photoresistance of two-dimensional electron gas

P. D. Ye[a] and L. W. Engel[b]
National High Magnetic Field Laboratory, Tallahassee, Florida 32310

D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno
Sandia National Laboratories, Albuquerque, New Mexico 87185

(Received 11 June 2001; accepted for publication 2 August 2001)

We measure microwave frequency (4–40 GHz) photoresistance at low magnetic field B, in high mobility two-dimensional electron gas samples, excited by signals applied to a transmission line fabricated on the sample surface. Oscillatory photoresistance vs B is observed. For excitation at the cyclotron resonance frequency, we find a giant relative photoresistance $\Delta R/R$ of up to 250%. The photoresistance is apparently proportional to the square root of applied power, and disappears as the temperature is increased. *© 2001 American Institute of Physics.*

[DOI: 10.1063/1.1408910]

The two-dimensional electron gas (2DEG) in GaAs/Al$_x$Ga$_{1-x}$As heterojunctions has long been known to exhibit resonant photoresponse to illumination at the cyclotron resonance frequency, f_C. This resonant response has generally been attributed to heating of the electrons by absorption of energy from the radiation field. The earliest photoresistance experiments on 2DEG, in both the far infrared[1,2] and millimeter wave[3] regimes, showed single, well-defined positive photoresistance features near the cyclotron resonance condition, $f=eB/2\pi m^*$, where f is the applied frequency and m^* is the effective mass in GaAs, and $eB/2\pi m^*$ is the cyclotron frequency, f_C. $\Delta R/R$, the change of dc resistance due to applying radiation, divided by the resistance with the radiation off, was much less than unity.

Later work[4] for $f=30$ to 150 GHz, used higher mobility samples ($\mu \sim 3\times 10^6\ \mathrm{cm^2/V\,s}$, about three times that in the earlier investigation),[3] and revealed ΔR of large relative size, with larger $\Delta R/R\approx 0.35$. Strikingly, ΔR vs B showed oscillations with alternating positive and negative ΔR. These ΔR oscillations were periodic in $1/B$ like Shubnikov–de Haas (SdH) oscillations, but had f-dependent period $e/m^*2\pi f$. ΔR peaks occurred at $f\approx jf_C$, for $j=1,2,3...$. The $j=1$ peak was largest but peaks for j up to 7 were observed. To explain the oscillatory photoresistance, the authors of Ref. 4 proposed a process in which impurity scattering combines with microwave absorption at jf_C. This causes transitions between Landau orbitals with energy quantum numbers differing by j and guiding centers displaced from each other.

In this letter we report on photoresistance measurements, in which microwaves were applied to a transmission line made of metal film on the top surface of the sample. We find an oscillatory $\Delta R/R$ whose maximum value is 2.5, nearly an order of magnitude larger than previously observed.[4] The giant photoresistance decreases with T, and is proportional to the incident microwave *amplitude*, that is, to the square root of the applied power.

We performed measurements on samples originally designed for broadband, transmission line based measurements of the microwave conductivity of the 2DEG.[5] Figure 1 is a schematic illustration of a sample. On the top surface of the 3×5 mm sample, a film of 200 Å Ti and 3500 Å Au was patterned to form a coplanar waveguide (CPW)[6] transmission line, with a 30 μm wide center strip separated from side ground planes by slots of 20 μm width, which are shown in light gray in Fig. 1. In the limit of low 2DEG conductivity, the in-plane microwave fields produced by driving the CPW are well-confined within the slots; in the present experiments some of the microwave field leaks under the metal film near the slot. We studied the change, on applying microwaves to the CPW, of quasi-dc resistance measured using combinations of the alloyed AuGe/Ni contacts at the edges, marked 1 through 8 in Fig. 1. The 2DEG under the tapers of the CPW at the edges of the sample (the areas indicated by the dashed lines in Fig. 1) was removed by chemical wet etching. The rest of the sample was not etched, so the ohmic contacts are connected to the slot areas by the 2DEG under the ground planes.

We measured two samples, both made from the same

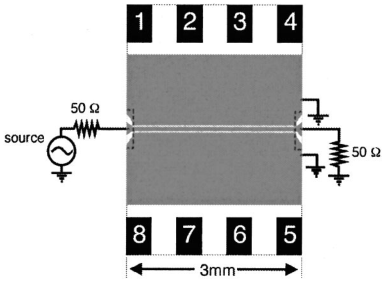

FIG. 1. Schematic view of sample and microwave connections is shown. Dark gray represents metal film and numbered black rectangles represent ohmic contacts. The slots are shown in light gray and contain antidots for sample 2 only. The sample is 5 mm long by 3 mm wide, and the edge of the ground plane is about 1 mm from the top edge of the sample.

---

[a] Also at Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544.

[b] Electronic mail: engel@magnet.fsu.edu

0003-6951/2001/79(14)/2193/3/$18.00

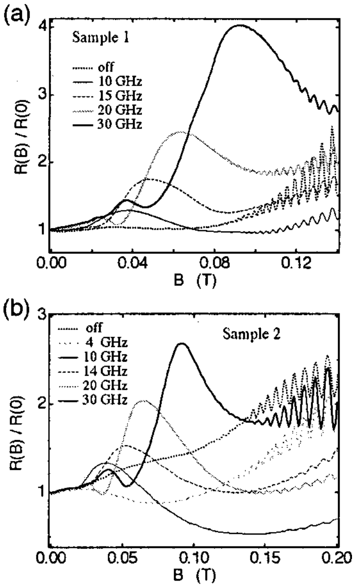

FIG. 2. Resistance R vs magnetic field B, for microwave excitation at various frequencies f is shown. Data are normalized to $B=0$ value $R(0)$. Reference traces taken with microwave power off are also included.

wafer, a high-mobility GaAs–AlGaAs heterojunction in which the 2DEG was located approximately 120 nm underneath the sample surface. Sample 2, but not sample 1, contained an antidot array, which was placed just in the two CPW slots. To produce the antidots, 500 nm period square lattices of 50 nm diameter and 50 nm deep holes were defined by electron beam lithography and reactive ion beam etching.[7] The samples were prepared for measurement with a brief illumination from a red light-emitting diode, after which 0.3 K mobility (without antidots) was around $3-4\times10^6\ \mathrm{cm}^2/\mathrm{V\,s}$. As determined from SdH oscillations in R vs B, the densities of sample 1 and sample 2 were, respectively, $1.7\times10^{11}\ \mathrm{cm}^{-2}$ and $2.1\times10^{11}\ \mathrm{cm}^{-2}$.

The quasi-dc resistance measurements used a typical operating frequency of 13.5 Hz, and an applied current of 100 nA root-mean-square. We report resistances, R, measured from four contacts along one edge of the sample, in the topology associated with diagonal resistivity, with injected current between contacts 1 and 4 in Fig. 1, and voltage taken between contacts 2 and 3. With the microwaves both off and on, some asymmetry of R between positive and negative B was present in sample 1, and to a much lesser extent in sample 2. We attribute this asymmetry to the inhomogeneity produced by illumination, and to the large size and close proximity to each other of the contacts. All the $R(B)$ presented here are the average of data taken at B and $-B$.

The samples were measured in a dilution refrigerator cryostat. A Hewlett Packard 8722D network analyzer at room temperature supplied microwave signals to cryogenically compatible coaxial cables that were connected to the CPW. The external magnetic field (B) was normal to the plane of the 2DEG.

Figure 2(a) shows R vs B for sample 1. Along with a reference trace taken with the microwave source off, traces are shown for several applied microwave frequencies, f. The microwave power P was 100 nW at 50 ohms, incident onto the edge of the CPW. The "bath" temperature (that of the metal on which the sample was mounted) was about 100 mK, but heating due to the applied power must have occurred. When microwaves are incident on the CPW, R vs B exhibits a series of peaks. As f increases, the oscillations shift to higher B and grow stronger, and more features emerge at lower B. For $f\geqslant20$ GHz, there are three peaks, which we will see have roughly even spacing in $1/B$.

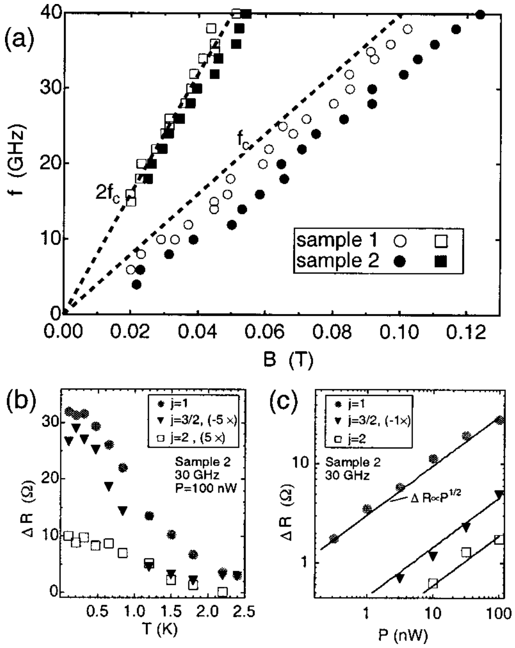

FIG. 3. (a) Microwave excitation frequency (f) plotted vs magnetic field (B) position of two largest photoresistance maxima and (b) 30 GHz ΔR, for $P=100$ nW vs cryostat temperature T are shown. ΔR is taken at maxima with $j=1,2$, and the minimum at $j=3/2$, where $f=jf_C$, and f_C is the cyclotron frequency. (c) Photoresistance ΔR for microwave frequency $f=30$ GHz vs power (P) at 50 Ω incident on the edge of the sample is shown. Cryostat temperature was $T\sim100$ mK. Lines show best fits to $\Delta R\propto P^{1/2}$.

Data for sample 2 (with antidots in the CPW slots) are shown in Fig. 2(b). The $1/B$ oscillations exist similar to sample 1. The different behavior of the two samples, both with and without the microwaves, are likely due to different red-light illumination doses rather than to the presence of the antidots in sample 2. The antidots have little effect on the measurement since the measuring contacts are all on one side of the antidot strips and so are somewhat remote from them.

Our main result is the *large size* of the photoresistance seen particularly on the highest B peak. There, we find $\Delta R/R$, the change in R on applying microwaves, divided by the microwaves-off value, as high as 2.5 for sample 1 and 2.0 for sample 2. The large $\Delta R/R$ can not be explained by R being made small by the cancellation of Hall and diagonal contributions to the measured resistance. So it is clear that the application of the microwaves near resonance produces a drastic change in the transport of the 2DEG.

The photoresistance oscillations are related to f as described in Ref. 4; with $f=jf_C$, maxima occur at integer j, and minima at half integer j. Figure 3(a) shows the positions of the $j=1$ and $j=2$ microwave-produced maxima of both samples. The applied frequency, f, is plotted against the B at which the maximum occurs. f_C and $2f_C$ are also plotted, where we have used m^* of 0.07 times the free electron mass. The maxima falling close to the lines demonstrates the approximate $1/B$ periodicity of the photoresistance oscillations. The highest $B(j=1)$ maximum falls at a significantly higher

B than the f_C line, especially for sample 2. The $j=2$ maximum falls on $2f_C$ to within about 5% for both samples. An outward shift of the first harmonic was also reported in Ref. 4.

In Fig. 3(b), we plot ΔR vs T for the $j=1,3/2$, and two photoresistance extrema of sample 2, for $P\approx 100\,\mathrm{nW}$, at $f=30\,\mathrm{GHz}$. ΔR is negative for $j=3/2$, and positive for $j=1$ and 2. $|\Delta R|$ increases with decreasing T, saturating around 500 mK. 30 GHz photons have energy k_BT at 1.43 K; ΔR vs T is significantly reduced from its maximum by that temperature, and is likely characterized by that energy.

Figure 3(c) shows ΔR vs P, the microwave power incident onto the CPW, for sample 2 with $f=30\,\mathrm{GHz}$, at the $j=1$ and $j=2$ maxima and the $j=3/2$ minimum. The bath temperature, T, to which the electrons cool in the limit of very small P applied, was around 100 mK. Lines with $\Delta R\propto P^{1/2}$ appear on the graph. This behavior fits the $j=1$ data well and is at least consistent with the data for $j=3/2$ and $j=2$. The $\Delta R\propto P^{1/2}$ behavior appears to hold well down to small P, where heating of the sample would be much less. ΔR vs P may be affected by (1) heating of the sample and by (2) reflectance of the CPW varying with P. The second effect could make the microwave intensity that reaches the relevant area of 2DEG nonlinear in the power incident onto the CPW.

The samples we looked at have similar mobility to those examined in Ref. 4. The high ends of our f and T ranges overlap the conditions studied in that reference, for example at $f=30\,\mathrm{GHz}$, $T=2$ K. The much larger $\Delta R/R$ presently observed may be due to a larger power density reaching the 2DEG, or to inhomogeneity caused by the opaque ground planes upon illuminating the sample with red light.

In conclusion, we have found a low-B microwave photoresistance much larger than previously observed. The features have apparent $P^{1/2}$ dependence, and a characteristic $T\sim hf/k_B$.

The authors would like to thank W. E. Baca, J. Wang, and J. Yao for technical assistance and C. M. Hu for valuable discussions. They especially thank R. R. Du for making Ref. 4 available before publication. This work is supported by the Air Force Office of Scientific Research and the National Science Foundation.

[1] J. C. Maan, T. Englert, and D. C. Tsui, Appl. Phys. Lett. **40**, 609 (1982).
[2] R. E. Horstman, E. J. van der Broek, J. Wolter, R. W. van der Heijden, G. L. J. A. Rikken, H. Sigg, P. M. Frijlink, J. Maluenda, and J. Hallais, Solid State Commun. **50**, 753 (1984).
[3] E. Vasiliadou, G. Müller, D. Heitmann, D. Weiss, K. von Klitzing, H. Nickel, W. Schlapp, and R. Lösch, Phys. Rev. B **48**, 17145 (1993).
[4] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, cond-mat/9711149; see also M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B (in press).
[5] L. W. Engel, D. Shahar, Ç. Kurdak, and D. C. Tsui, Phys. Rev. Lett. **71**, 2638 (1993); *Physical Phenomena in High Magnetic Fields II, Proceedings* (World Scientific, Singapore, 1996), p. 23.
[6] C. P. Wen, IEEE Trans. Microwave Theory Tech. **17**, 1087 (1969).
[7] G. A. Vawter, in *Handbook of Advanced Plasma Processing Techniques*, edited by R. Shul and S. Pearton (Springer, Berlin, 2000), p. 50.