The two dimensional electron gas (2DEG) in GaAs/Al_xGa_{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 (FIR) and millimeter wave (mmw) 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 for $f = 30$ to 150 GHz, used higher mobility samples ($\mu \sim 3 \times 10^6$ cm$^2$/Vs) with electron densities of sample 1 and 2 being 1.7 and 2.1 $\times 10^{11}$ cm$^{-2}$, respectively. The quasi-dc resistance measurements used typical op-amps and sample 2 was respectively 1.7 and 2.1 $\times 10^{11}$ cm$^{-2}$. The $\Delta R/R$ peaked at $f \approx j f_c$ for $j = 1, 2, 3, \ldots$. The $j = 1$ peak was largest but peaks for $j > 7$ were observed. To explain the oscillatory photoresistance the authors of ref. [4], proposed a process in which impurity scattering combines with microwave absorption at $j f_c$. This causes transitions between Landau orbitals with energy quantum numbers differing by $j$ and guiding centers displaced from each other.

In this paper 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. The giant photoresistance decreases with $T$, and is proportional to the incident microwave amplitude, that is, to the square root of the applied power.
associated with diagonal resistivity, with injected current between contacts 1 and 4 on 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 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.

Fig. 2a 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 $f \geq 20$ GHz there are three peaks, which we will see have roughly even spacing in $1/B$.

Data for sample 2 (with antidots in the CPW slots) are shown in Fig. 2b. 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 $\Delta R/R$ cannot be explained by $R$ being made small by 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. [1]; with $f = j f_C$, maxima occur at integer $j$, and minima at half-integer $j$. Fig. 3a 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 $2 f_C$ are also plotted, where we have used $m^* = 0.07$ 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 significantly higher $B$ than the $f_C$ line, especially for sample 2. The $j = 2$ maximum falls on $2 f_C$ to within about 5 percent for both samples. Outward shift of the first harmonic was also reported in ref. [2].

In Fig 3b, we plot $\Delta R$ vs $T$ for the $j = 1, 3/2$, and 2 photoresistance extrema of sample 2, for $P \approx 100$ nW, at $f = 30$ GHz. $\Delta R$ 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 $k_B T$ at 1.43 K; $\Delta R$ vs $T$ is significantly reduced from its maximum by that temperature, and is likely characterized by that energy.

Fig. 3c shows $\Delta R$ vs $P$, the microwave power incident onto the CPW, for sample 2 with $f = 30$ 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 down well to small $P$, where heating of the sample would be much less. $\Delta R$ 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. [1]. The high ends of our $f$ and $T$ ranges overlap the conditions studied in that reference, for example at $f = 30$ 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 $T \sim h f / k_B$.

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FIG. 1: Schematic view of sample and microwave connections. Dark gray represents metal film, 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.

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

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