High Magnetic Field Microwave Conductivity of 2D Electrons in an Array of Antidots

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We measure the high magnetic field ($B$) microwave conductivity, $\operatorname{Re}(\sigma_{xx})$, of a high mobility 2D electron system containing an antidot array. $\operatorname{Re}(\sigma_{xx})$ vs frequency ($f$) increases strongly in the regime of the fractional quantum Hall effect series, with Landau filling $1/3 < \nu < 2/3$. At microwave $f$, $\operatorname{Re}(\sigma_{xx})$ vs $B$ exhibits a broad peak centered around $\nu = 1/2$. On the peak, the 10 GHz $\operatorname{Re}(\sigma_{xx})$ can exceed its dc-limit value by a factor of 5. This enhanced microwave conductivity is unobservable for temperature $T > 0.5$ K, and grows more pronounced as $T$ is decreased. The effect may be due to excitations supported by the antidot edges, but different from the well-known edge magnetoplasmons.

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Collective excitations of a two dimensional electron system (2DES) patterned with arrays of microscopic, artificial structures, have long been of particular interest since they can be richer than those of unpatterned 2DES, whose long-wavelength dipolar excitations are constrained by Kohn’s theorem\textsuperscript{1} to show no effect of electron-electron interaction. One role of the artificial structures is to couple electromagnetic radiation to the 2DES at enhanced wavevector, $q$, resulting for example in the observation of 2D plasmons\textsuperscript{2} in far infrared (FIR) optical experiments. In other cases the artificial structures support excitations not easily understood as finite-$q$ plane wave modes of the free 2DES. An array of antidots (small regions from which electrons are excluded) applied to a 2DES exhibits such an excitation\textsuperscript{3}, an edge magnetoplasmon encircling the antidots, at much lower frequency than the cyclotron resonance. We now report a microwave-frequency excitation of antidot arrays that occurs only in the low temperature ($T$), high magnetic field ($B$) regime of the fractional quantum Hall effect (FQHE)\textsuperscript{4}.

Patterning 2DES with antidot or other nanostructure arrays has also resulted in striking effects in dc transport. Best known are the commensurability oscillations\textsuperscript{5} in low $B$, which result from semiclassical ballistic scattering of electrons off the array structures. In an antidot lattice, such “geometric resonance” oscillations appear as resistance peaks at $B$’s where the cyclotron orbit of radius $R_c$ encircles an antidot or group of antidots. In a development of consequence for the understanding of the FQHE, commensurability oscillations have also been observed\textsuperscript{6} in high $B$, near Landau filling $\nu = 1/2$. These high-$B$ oscillations are naturally described by composite fermions (CF’s)\textsuperscript{7} and exotic particles that contain the electron-electron interaction responsible for the FQHE, and that can (for $\nu \sim 1/2$) be thought of as an electron bound up with two flux quanta. Near $\nu = 1/2$ the CF’s move in an effective magnetic field, $B_{eff} = B - B_{c1/2}$, and the resulting CF cyclotron orbits of radius $R_c = \hbar (4\pi n_s^{1/2})/eB_{eff}$, where $n_s$ is the 2DES carrier density, can encircle one antidot or more, resulting in geometric resonance resistance peaks.

This paper presents high $B$, finite-frequency measurements of 2DES patterned with nanostructure antidot lattices. The frequency ($f$) is varied between 0.1 and 10 GHz, for temperature $T > 100$ mK, to cover a previously unexplored regime between the dc and FIR experiments. For $f$ above about 2 GHz, over a broad range of $\nu$, centered around 1/2, we find that the measured diagonal conductivity of the array, $\operatorname{Re}(\sigma_{xx})$, increases with $f$—by as much as a factor of five at 10 GHz. Surprisingly, the antidot array in this regime has microwave conductivity increasing with $f$ while decreasing with $T$. The enhanced microwave conductivity (1) is present only in the FQHE regime $\nu < 1$, and at high $f$ appears in $\operatorname{Re}(\sigma_{xx})$ vs $B$ as a striking broad peak roughly symmetric around $\nu = 1/2$ and (2) requires $T < 0.5$ K, and increases as $T$ is reduced down to 100 mK. In contrast, the $\nu \sim 1/2$ dc-limit conductivity in the same sample is essentially $T$-independent below 1 K. Since the enhanced microwave conductivity is produced by the antidots, and has $T$ dependence so unlike the dc conductivity, we attribute it to states at the antidot edges which are driven directly by the microwave field.

Our samples were prepared from GaAs-AlGaAs heterojunctions where the 2DES was located approximately 120 nm underneath the sample surface. With the antidots, after low $T$ red LED illumination, carrier density, $n_s$, was $1.1 \times 10^{11}$ cm$^{-2}$. We also measured a reference sample from the same wafer, but without antidots. Without antidots, this wafer had typical, 0.3 K electron mobility of around $\mu \approx 3.6 \times 10^{6}$ cm$^2$/Vs.

Fig. 1(a) shows a sketch of the sample with antidots. On its top surface, 200 Å Ti and 3500 Å Au were patterned to form a 2 mm long planar transmission line, consisting of a 30 µm wide center strip separated from...
FIG. 1: (a) Top view of sample showing coplanar waveguide transmission line (metal film is dark grey) deposited on top of sample. Ohmic contacts are at the (edges (black), and two antidot patterned areas (light grey) are in slots. The right part is electron micrograph of the antidot array. (b) microwave absorption for $a = 500$ nm antidot lattice. Geometric resonances due to orbits encircling 1 and 4 antidots are marked.

side planes by 20 μm-wide slots. These slots contain the antidot array, a square lattice with period $a = 500$ nm. Holes with diameter 50 nm were defined by electron beam lithography and reactive-ion-beam etching. We report on a sample etched to 50 nm depth; 30 and 70 nm depths gave comparable results. The depleted region around an antidot is much larger than the lithographically defined hole in the wafer; we estimate the depletion region diameter to be 150 to 250 nm. The 2DES in the areas enclosed by the dashed lines in Fig.1(a) was removed by wet etching.

The microwave measurement methods used here are similar to those described in earlier publications. $\text{Re}(\sigma_{xx})$ is calculated from the effect of the 2DES on microwave propagation through the transmission line which couples capacitively to the 2DES. In the present work, a room-temperature source and receiver are connected to the transmission line by cryogenic coaxial cables. $\text{Re}(\sigma_{xx})$, the real part of the diagonal conductivity of the 2DES, is related to the transmitted power, $P$, $\text{Re}(\sigma_{xx}) = W|\ln(P/P_0)|/2Z_0d$, where $d = 2$ mm is the total length of the transmission line, $W = 20\mu$m is the width of a slot, $P_0$ is the transmitted power for $\sigma_{xx} = 0$, and $Z_0$ is 50 Ω, which is the characteristic impedance for the $\sigma_{xx} = 0$ case. Detailed analysis of the system in the quasi-TEM approximation (including reflections, distributed capacitive coupling, and the effect of the 2DES on the true characteristic impedance of the line) shows an $f$ (but not $T$ or $B$) dependent systematic error of about ±15 percent in the $\text{Re}(\sigma_{xx})$ taken from this formula. The determination of $P_0$ produces an additional experimental uncertainty in $\text{Re}(\sigma_{xx})$ for $f > 2$ GHz. This “normalization error” varies strongly with $f$ but is independent of $B$ and $T$. We estimate it as to ±0.4 μS for $f > 2$ GHz.

The in-plane microwave electric field is largely confined to the slots, so $\text{Re}(\sigma_{xx})$ characterizes the 2DES in the slots, where the antidot pattern exists.

At low $B$, both microwave transmission and dc magnetoresistance show the well-known commensurability oscillations between the electron cyclotron radius and the period of the antidot array. Fig. 1(b) shows 1 GHz microwave power, $P$, sent through the transmission line, vs $B$ in the low magnetic field range. Electron geometric resonances appear for cyclotron orbits circling one and four antidots, indicating that in between the antidots there is low-disorder 2DES, characterized by mean free path $\gtrsim 3\mu$m.

We now focus on high magnetic fields, especially the range $2/3 < \nu < 1/3$, for which we obtained our main results. Fig. 2(a) shows traces $\text{Re}(\sigma_{xx})$ vs $B$ for several frequencies $f$. At the lowest $f$ of 0.1 GHz, the trace shows features well-known from dc transport, with several dips in $\text{Re}(\sigma_{xx})$ coming from the FQHE, including the 3/7 and 4/7 FQH states. Around $\nu = 1/2$ ($B = 8.5$ T), this trace exhibits a small peak which is marked “CF” in the figure, since it is likely an effect of the CF Fermi surface. This peak is absent in the sample without the antidots. We ascribe this small peak to the antidots or to residual disorder induced by the antidot lithography. $\text{Re}(\sigma_{xx})$ vs $B$ shows no geometric resonances corresponding to CF cyclotron orbits around antidots; observation of these resonances requires lower disorder samples.

Our main result appears in the successively higher-$f$ traces of Fig. 2(a). Around 8.5 T, where $\nu = 1/2$, $\text{Re}(\sigma_{xx})$ vs $B$ develops a broad maximum, which dominates the conductivity at high $f$. $\text{Re}(\sigma_{xx})$ clearly increases monotonically with $f$ in the $B$ range of this maximum from $B$ just above the 2/3 FQHE minimum up to our highest $B$ just below the 1/3 effect. The $f$ dependence is more complicated for $B$ just above the $\nu = 1$ integer quantum Hall effect (IQHE), where $\text{Re}(\sigma_{xx})$ apparently decreases with $f$ between 0.1 and $\sim 4$ GHz. The data in Fig. 2(b) show that the strong frequency response of the conductivity only exists for $T < 0.5$ K. Fig. 2(b) shows $\text{Re}(\sigma_{xx})$ vs $B$ for $f = 8$ GHz, measured at several temperatures. The broad $\nu \sim 1/2$ maximum in $\text{Re}(\sigma_{xx})$ vs $B$ disappears gradually as the temperature is increased; the peak height is roughly halved at 200 mK, and the peak is unobservable at 600 mK.

In Fig. 2(a), the normalization error is small for the 0.1 GHz trace, and can only shift the other traces by $B$-independent constants, estimated to be within ±0.4 μS. Normalization error, which is independent of $T$ as well as of $B$ could uniformly shift all the curves together in Fig. 2(b) by ±0.4 μS.

Fig. 3 summarizes the trends evident from Fig. 2. $\text{Re}(\sigma_{xx})$ vs $B$ at $T \approx 100$ mK is plotted in Fig. 3(a) for $\nu = 1/2, 2/3, 3/5$ and 2/5. For the reference sample lacking antidots (open symbols, dotted line), the error
the reference sample and the antidot sample have some dependence is clearly associated with the antidots. Both QHE minima, but only the antidot sample shows the insensitivity at the edges of and around transitions between 

Recent theoretical work [12] applicable to transport and to magnetic scattering of electrons in a disorder potential, points out corrections to the Drude model. For $\omega \tau << 1$, and weak random potentials, that theory predicts increasing Re($\sigma_{xx}$) vs $f$ at $\nu = 1/2$.

Delocalized CF’s must exist between the antidots to cause the dc-limit conductivity, but cannot explain the $T$-dependence of the high-$f$ peak in Re($\sigma_{xx}$) vs $B$. As shown in Fig. 3(b), the low $f$, $\nu = 1/2$ conductivity is essentially $T$ independent for $T \lesssim 1$ K. Hence scattering that leads to dc resistance at $\nu = 1/2$ is not causing the increase of Re($\sigma_{xx}$) at high $f$, which is strongly reduced even at 200 mK.

Since the enhanced microwave absorption is produced by the antidots, it is reasonable to assume it arises from states at the antidot edges. These states would couple to the microwave field, to contribute to transport at microwave frequencies, but not at dc. Changes in the configuration of the edge states, or in their ability to dissipate microwave power would then be responsible for the $T$ dependence of the observed high $f$ Re($\sigma_{xx}$). No peak in the spectrum is observed, so the measurement can be interpreted as a lossy dielectric response, effectively accessing just the low $f$ tail of edge modes.

The present experiment operates in a different regime than previous edge spectroscopy [8, 11], and may access edge modes of novel type. The microwave frequency and temperature are lower than in FIR [8, 11] investigations, and the antidot edges are much shorter than...
the edges looked at in ref. [14] or pulsed experiments [15, 16] on large QHE samples. Besides accessing large wavevectors, the smallness of the antidots can make the present measurement sensitive to modes that would be completely damped out on macroscopic edges.

The states at the edges of quantum Hall systems depend on the softness of the edge potential profile. The edge potential of the etched antidots in our sample must vary slowly on the scale of the magnetic length, $(\hbar/eB)^{1/2}$, and so is expected to undergo reconstruction into alternating compressible and incompressible strips [7]. Because we observe well-defined FQHE states there are apparently regions between the antidots that are well-characterized by bulk states. The antidot depletion diameter (150-250 nm) and lattice constant (500 nm) then constrain the length over which strips could develop.

While much is not understood about quantum-Hall edges, tunneling experiments [18, 19] have revealed behavior of fractional-regime edges that matches the chiral Luttinger liquid description of FQHE edges [20], and distinct, non-interacting Fermi liquid behavior of IQHE edges [20], while the smallness of the antidots can make the present microwave data. First, like the microwave absorption the tunneling behaves differently in the fractional regime, $\nu < 1$, than it does higher $\nu$. With $\nu < 1$, $\alpha$ takes the value $(\nu^{-1} - 1)$, and as had been predicted for a chiral Luttinger liquid based theory [20], while $\alpha$ is roughly unity for $\nu > 1$ [14]. Second, $\alpha$ has been observed to vary continuously according to this formula as $\nu$ is swept [14]. This tunneling behavior holds continuously for a range of $\nu$, including 1/2, that is essentially the same as that for which we observe enhanced microwave absorption.

Finally, we cannot rule out more exotic states of the antidot edges as explanations of the low $T$ microwave absorption. Edge modes coupled with phonons in the host semiconductor have been predicted theoretically [21], and would likely be quite sensitive to $T$. Edge charge density waves (Wigner crystal) [22] have been predicted to develop at QHE edges, and could be $T$ sensitive. Coupling between edges of neighboring antidots could play a role in modes of an antidot array like that studied here.

In conclusion, we observe an anomalous microwave response vs $f$ on antidot patterned 2DES at high magnetic fields. The observed $T$-dependence suggests that the effect is associated with the edges of the antidots.

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