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Microwave photoresistivity of a two-dimensional electron gas and the fractional quantum Hall effect

Y. Guldner, M. Voos, J. P. Vieren, and J. P. Hirtz*
Groupe de Physique des Solides de l'Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France

M. Heiblum
IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
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We describe experimental results obtained from microwave photoresistivity measurements in a low-electron-density modulation-doped GaAs-$Al_xGa_{1-x}As$ heterojunction. We believe that such sensitive experiments can provide interesting information on the fractional quantum Hall effect.

Photoconductivity measurements in GaAs-$Al_xGa_{1-x}As$ heterojunctions under microwave and far-infrared illumination have been previously performed to study the electron cyclotron resonance[1] and the electric-dipole-induced electron spin resonance.[2,3] Shubnikov–de Haas–like oscillations of the microwave and far-infrared photoconductivity have also been previously reported in GaAs-$Al_xGa_{1-x}As$ heterojunctions[3] and Si metal-oxide-semiconductor field-effect transistors (MOSFET's).[4] A strong enhancement of the photosignal around the magnetic field corresponding to the cyclotron resonance is usually observed.[5]

We wish to report here microwave photoresistivity measurements performed in a modulation-doped GaAs-$Al_xGa_{1-x}As$ heterojunction grown by molecular-beam epitaxy and exhibiting at 1.3 K an electron density n and mobility μ equal to 5×10^{10} cm^{-2} and 500 000 $cm^2\,V^{-1}\,s^{-1}$, respectively. The sample used in these experiments presents therefore an extremely diluted two-dimensional electron gas, so that the quantum limit, where the last Landau level is the only populated one, could be reached at rather low magnetic field ($B\sim2$ T). Oscillations of the microwave photoresistivity are observed in this sample for integer values of the filling factor $\nu=nh/eB$ and also for the fractional values $\nu=\frac{1}{3},\frac{2}{3},\frac{4}{3},\frac{5}{3}$.

The sample geometry was simply a 2×2-mm^2 square with two opposite contacts so that the different components of the resistivity tensor (ρ_{xx} and ρ_{xy}) could not be individually examined in such a structure. The microwave sources were carcinotrons with frequency ranging from 100 to 500 GHz. The bias current could be adjusted between 30 nA and 1 μA. The sample was cooled down to 1.3 K, and the magnetic field was provided by a 10-T superconducting coil. Changes in the sample resistance due to the chopped radiation (80 Hz) were detected by using a lock-in amplifier.

Let us note at first that cyclotron-resonance experiments performed on this heterojunction demonstrate its high quality. Typical data obtained at 1.6 K for different infrared wavelengths λ are given in Fig. 1. For example, the cyclotron resonance line obtained for $\lambda=118$ μm yields $0.0685m_0$ for the electron effective mass and is very narrow since its half width at half maximum is about 500 G. The asymmetrical shape of the cyclotron-resonance lines is due to far-infrared interferences within the substrate which do not affect significantly the linewidth.

Figure 2 shows the dc resistivity ρ of the sample as a function of the magnetic field B at 1.3 K. Although the sample geometry was not a Hall bridge, the sample resistivity versus B looks like a usual quantum Hall curve[6,7] for reasonably high magnetic fields ($B>0.5$ T). This is due to the high mobility of the sample which implies $\rho_{xx}\ll\rho_{xy}$ for large magnetic fields. The resistivity plateaus are well developed for $\nu=1,2$ and a deviation from the linear relation $\rho=B/ne$ is observed at rather high magnetic field ($B\sim6.5$ T) and corresponds to $\nu=\frac{1}{3}$. This deviation is related to the plateau $\rho=3h/e^2$ which would be observed[8] at lower temperatures. No significant feature

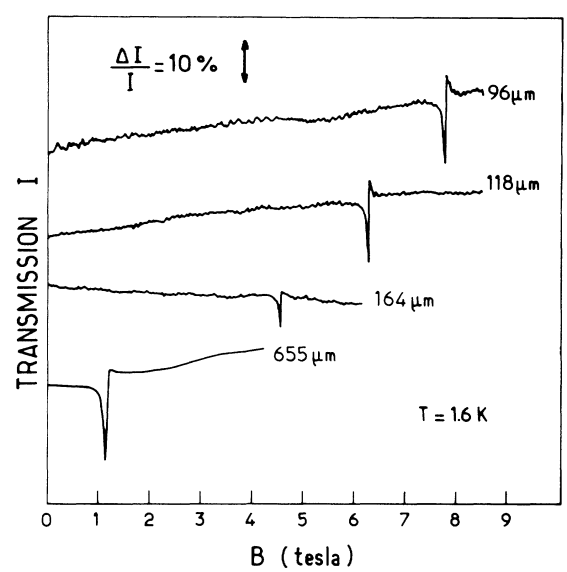

FIG. 1. Typical transmission spectra at 1.6 K as a function of the magnetic field B for different infrared wavelengths.

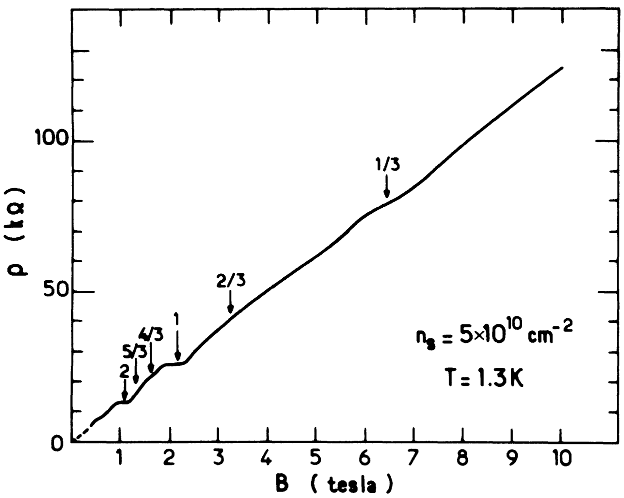

FIG. 2. dc resistivity ρ as a function of the magnetic field B at 1.3 K. Different values of the filling factor ν are indicated by arrows.

is detected for $\nu=\frac{2}{3}$ at this temperature. Very small deviations appear around $B\sim1.5$ T which corresponds to the crossover of the Landau level $N=0^-$ with the Fermi energy. These deviations may be connected to the existence of structures at $\nu=\frac{4}{3}$ and $\frac{5}{3}$. Figure 3 shows the photoresistivity signal $\Delta\rho$ as a function of the magnetic field, i.e., the variation of the resistivity under microwave radiation provided by a carcinotron whose frequency and output power were here equal to 110 GHz ($\lambda=2.7$ mm) and 100 mW, respectively. Pronounced oscillations are observed in the whole magnetic field range, but a strong enhancement of the detected signal can be seen around the magnetic field of the cyclotron resonance ($B\sim0.3$ T). This occurs because the source of the photosignal is certainly electronic heating which is increased at the cyclotron-resonance magnetic field. Apart from this effect, the position of the oscillations corresponds approximately to that which can be expected if the sample is heated by the microwave radiation. Ideally, when a true Hall bridge is used, the photosignal may be expected to change sign across the Hall step. In this case, the photosignal $\Delta\rho$ would be maximum on the low-magnetic-field side of each Hall step and minimum on the high-magnetic-field side of the Hall steps. The step centers ($\nu=1,2,3,\ldots$) would thus correspond to the half amplitude of the oscillations. Here $\Delta\rho$ is always positive and the position of the oscillations corresponds only approximately to the one described above, which is likely to result from the geometry of our sample.

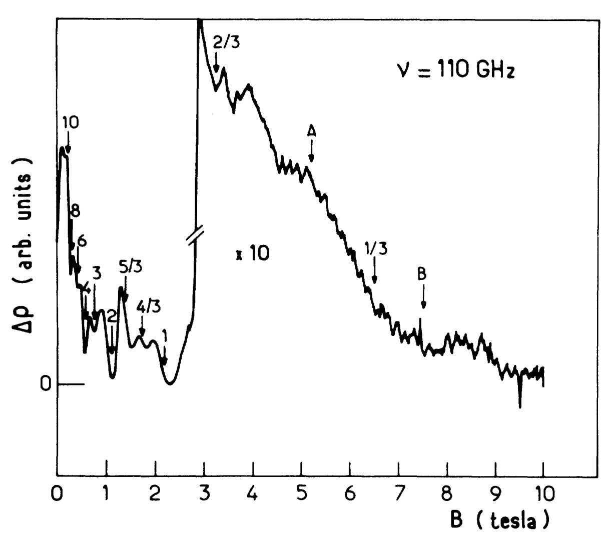

FIG. 3. Photoresistivity signal $\Delta\rho$ as a function of B obtained at 1.3 K under microwave radiation at 110 GHz. The arrows correspond to different filling factors ν.

In addition to those involving integer values of ν, two additional oscillations are observed and correspond to $\nu=\frac{5}{3}$ and $\frac{4}{3}$. It is noteworthy that these features are much more pronounced on the photoresistivity signal than those observed in dc resistivity (Fig. 2). A similar effect appears around $\nu=\frac{1}{3}$, where a maximum (A) and a minimum (B) of $\Delta\rho$ are distinguishable on both sides of the $\rho=3h/e^2$ Hall step. The photosignal is about ten times smaller in this region which is far from the cyclotron-resonance magnetic field. A maximum and a minimum of $\Delta\rho$ can even be observed around $\nu=\frac{2}{3}$. It is important to point out that the photosignal behaves in a similar way for Hall steps occurring at integral and fractional values of ν. We have also performed such experiments with a carcinotron whose frequency was 470 GHz ($\lambda=640$ μm) but, in this case, the corresponding carcinotron output power was of the order of 10 mW. Similar oscillations are observed for $\nu=2,3,4$ and $\frac{5}{3}$ in the region of the magnetic field of the cyclotron resonance ($B\sim1.15$ T), but nothing appears near $\nu=\frac{2}{3}$ and $\frac{1}{3}$ which correspond to magnetic fields (i.e., $B\sim3$ and 6 T, respectively) far away from the cyclotron resonance, where $\Delta\rho$ becomes less than the background noise. Large microwave powers are probably necessary to observe photosignal oscillations in the whole range of magnetic field investigated here.

There is strong interest in measuring[9–18] and calculating[19–35] the activation energies for quasiparticle excitations in the fractional quantum Hall effect.[8] We wish to point out (i) that the infrared photon energy corresponding to the 110-GHz radiation used here is $h\nu=0.45$ MeV which, depending on the magnitude of the magnetic field B, is somewhat larger or comparable to the values of the activation energy Δ found[13] recently by Boebinger *et al.* for $\nu=\frac{1}{3}$, $\frac{2}{3}$, $\frac{4}{3}$, and $\frac{5}{3}$; (ii) that our data exhibit features at 1.3 K for $\nu=\frac{4}{3}$ and $\frac{5}{3}$ for $B<2$ T, while the experiments of Boebinger *et al.* yield[13] $\Delta\sim0$ for $B<5$ T. It is likely that there is a nonzero activation energy for the quasiparticles in the conditions used here, which means that our sample is certainly of high quality from the viewpoint of the coupled values of the electron density and mobility.

To conclude, these investigations show that microwave photoresistivity experiments can provide significant information about the resistivity accidents occurring at fractional values[8] of the filling factor ν. The features at fractional values of ν are more pronounced in the photosignal than in the dc resistivity, at least when the microwave power is rather large. We believe finally that the method used here might be interesting and fruitful to study the activation energies associated to the fractional quantum Hall effect, especially if lower temperatures can be reached.

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*Present address: Laboratoire Central de Recherche, Thomson-CSF, 91401 Orsay, France.

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