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Measurements of the temperature dependence of the bubble phase

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Abstract

We examine the temperature dependence of the bubble phase using the resonance in the real diagonal conductivity, Re[σ_{xx}], discovered recently by Lewis et al. (Phys. Rev. Lett. 89 (2002) 136804). The peak frequency, $f_{\rm pk}$, of the resonance at base temperature of 30 mK is as much as 50% larger than at the highest temperature where a resonance is discernable. The resonance vanishes above a temperature of 80–100 mK.

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In the vicinity of filling factor $\nu = \frac{9}{2}$, clean two-dimensional electron systems (2DES) show anisotropic conductivity when the temperature is below $\sim$ 100 mK [1,2]. In addition, at $\nu \approx 4 + \frac{1}{4}$ and $4+\frac{3}{4}$, extra minima appear in the magnetoconductance which show quantized Hall conductance $\sigma_{xy} = e^2/4h$ and $e^2/5h$, respectively, and hence are not part of the series of fractionally quantized states seen at higher magnetic field (B). These minima have been dubbed the re-entrant integer quantum Hall effect (RIQHE) [3] and are thought to be caused by the formation of an isotropic charge density wave, an electronic crystal with a triangular lattice. This proposed phase is similar to the Wigner crystal (WC) [4,5] in these respects but allows for multiple electron occupancy of each lattice site [6–9], and hence goes by the name of "bubble phase".[2] Recently, Lewis et al. [10] have observed a resonance in the frequency dependence of the real diagonal microwave conductivity Re[σ_{xx}], at ν coincident with the RIQHE (from $0.2 \leqslant \nu^* \leqslant 0.38$, where $\nu^* = \nu - [\nu]$ and $[\nu]$ is the greatest integer less than the current value of ν). They interpret their results as due to the pinning mode of an isotropic electron crystal [11] in qualitative agreement with the proposed bubble phase.

Here we present measurements of the temperature, T, dependence of the resonance in Re[σ_{xx}] at $\nu = 4.32, 5.32$ and 6.32 from 30 mK until the resonance

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[2] For reviews of the Wigner crystal see Chapter 3 by H. Fertig and Chapter 9 by M. Shayegan of *Perspectives*.

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vanishes in the 80–100 mK, range. This extends the range of T studied in Ref. [10] downward by almost a factor of 2. We find the peak frequency, f_{pk}, decreases by as much as 50% as temperature increases and that a steady decrease in f_{pk} occurs in at least 3 different Landau levels.

The sample used in these experiments is a 300 Å GaAs/AlGaAs quantum well grown by molecular beam epitaxy. It has density $n = 3.0 \times 10^{11}$ cm^{-2} and mobility $\mu = 2.4 \times 10^7$ cm^2 V^{-1} s^{-1}. The 2DES resides some 2000 Å below the surface. The microwave measurement circuit [12] is made by patterning a coplanar wave guide (CPW) onto the sample surface through standard photolithography and thermal evaporation. In the high field limit, the small conductivity of the 2DES enters directly into the propagation constant of the microwave signal along the CPW and hence, the real part of the diagonal conductivity is given by $\mathrm{Re}[\sigma_{xx}] = w/(2lZ_0)\ln(P/P_0)$, where P is the transmitted power, P_0 is the power transmitted in the absence of a 2DES, $Z_0 = 50\ \Omega$, and $w/2l$ is the inverse number of squares in the CPW. This sample used $l = 4$ mm and $w = 80$ µm. The sample was mounted onto a metal block in the high B region on the tail of a dilution refrigerator. Thermal contact to the mixing chamber was provided by a bundle of high conductivity copper wires clamped to the block and temperatures were measured by a resistor mounted on the block. To avoid heating the sample, the applied microwave power was raised while at base temperature, until heating was observed. Data were taken below that level.

In the lower panel of Fig. 1, we show data for $\mathrm{Re}[\sigma_{xx}]$ versus frequency f measured at $\nu = 4.32$ for several block temperatures, T_b, between 30 and 110 mK. At 30 mK, the resonance peaks at $f_{pk} = 196$ MHz $\pm$ 5. As the sample is warmed, f_{pk} decreases. At 40 mK $f_{pk} = 190$ MHz; it is 180 MHz at 50 mK. The decrease in f_{pk} becomes more marked at higher temperatures, for instance, f_{pk} is just 100 MHz at 100 mK, the highest T_b for which we are able to reliably discern a peak. The upper panel of Fig. 1 is a greyscale plot in the T_b versus f plane of the resonance at $\nu = 4.32$ with data spaced in roughly 5 mK increments. Black corresponds to 0 conductivity and white to about 50 µS. We superimpose contours of constant $\mathrm{Re}[\sigma_{xx}]$ at 5 µS intervals for $\mathrm{Re}[\sigma_{xx}] \geqslant 10$ µS.

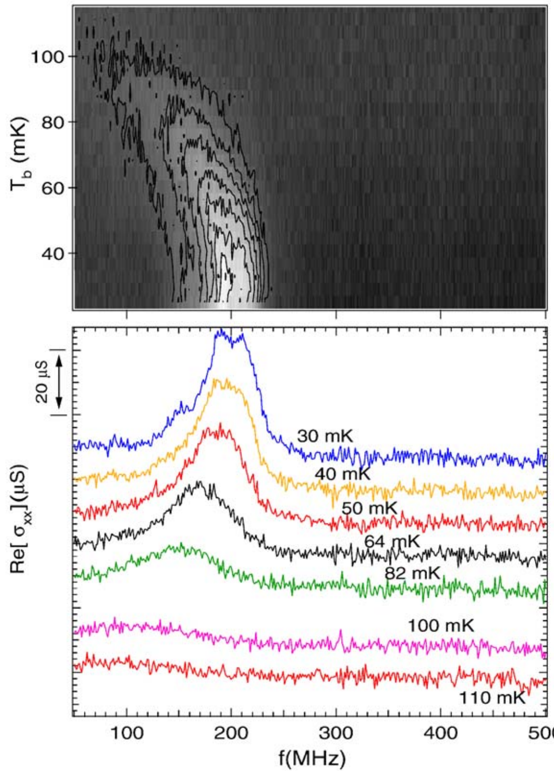

Fig. 1. Lower: The real part of the diagonal conductivity, $\mathrm{Re}[\sigma_{xx}]$ versus f taken at $\nu = 4.32$. Data at block Temperature, $T_b = 30, 40, 50, 64, 82, 100$, and 100 mK are shown offset for clarity. Upper: Grayscale plot of the same data in the T versus F plane. Contours in 5 µS steps beginning at 10 µS are superimposed.

Fig. 2 shows f_{pk} versus T_b for the resonance at $\nu = 4.32, 5.32$, and 6.32 between 25 and 100 mK. The data change smoothly with T_b down to about 40 mK, however, decreasing T_b below 30 mK yields no further change in the data, indicating that the 2DES does not cool below this point. The 2DES may not reach complete thermal equilibrium with the block at the lowest temperatures shown here. The resonance at $\nu = 5.32$ shows a decrease in f_{pk} from 320 MHz at 30 mK to 190 MHz at 80 mK, the highest temperature at which the resonance is visible for this ν. At $\nu = 6.32$, the resonance decreases from $f_{pk} = 420$ MHz at 30 mK down to about 250 MHz at 85 mK. This decrease of f_{pk} with T_b is consistent for all three data sets. The highest temperature at which a resonance was observable was between 80 and 100 mK, in rough agreement

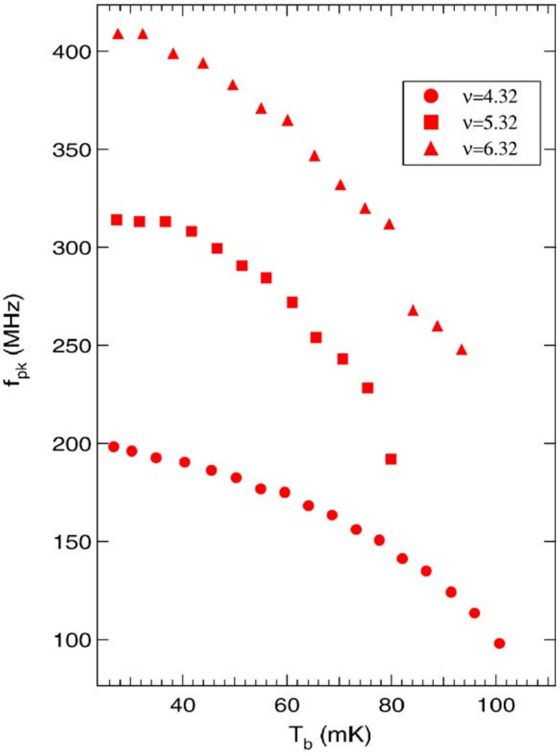

Fig. 2. Peak frequency, f_{pk} versus T for filling factors $\nu = 4.32, 5.32$, and 6.32. The error in f_{pk} is roughly the same as the symbol size.

with DC measurements of the RIQHE [3]. The error in f_{pk} is comparable with the symbol size.

We interpret the dependences of f_{pk} as follows. A decrease in f_{pk} as T increases may be due to a weakening of the effective pinning potential. It is conceivable that some pinning centers, of which there may be many in a single crystalline domain, pin less effectively at elevated T. In the context of weak pinning, a softening of the bubble crystal, i.e. a decrease in the shear modulus, would tend to increase f_{pk} which is contrary to our data [11].

In summary, we have presented data on dependence of the bubble phase resonance on temperature between 30 and 100 mK. Warming causes a decrease in f_{pk} with the resonance disappearing in the 80–100 mK, range. The change in f_{pk} between 30 and 100 mK can be as large as 50% of its base temperature value.

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