Antilevitation of Landau levels in vanishing magnetic fields

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(Received 15 April 2016; revised manuscript received 28 September 2016; published 17 October 2016)

We report in this Rapid Communication an antilevitation behavior of Landau levels in vanishing magnetic fields in a high quality heterojunction insulated-gated field-effect transistor. We found, in the Landau fan diagram of electron density versus magnetic field, the positions of the magnetoresistance minima at Landau-level fillings \( \nu = 4 \rightarrow 6 \) move below the “traditional” Landau-level line to lower electron densities. Moreover, the even and odd filling factors show quantitatively different behaviors in antilevitation, suggesting that the exchange interactions may be important.

DOI: 10.1103/PhysRevB.94.161303

Soon after the discovery of the quantum Hall effects (QHEs) [1,2] in two-dimensional electron systems (2DESs) in high magnetic fields, it was realized that the topological order [3–5] is important in understanding their profound implications. Indeed, unlike all previously known broken symmetry physics, no conventional symmetries are broken in the QHEs. Instead, a new order, the topological order, has to be evoked. It is this topological property that makes the quantization of Hall plateaus insensitive to sample geometries, impurities, densities, etc. In the integer quantum Hall (IQH) effect, the topological property can be quantified by the so-called Chern numbers, originally located at the band center, move down as the magnetic field is swept while the magnetic field is fixed. Details of converting on-site random disorder potentials, a surprising antilevitation behavior was observed from numerical investigations [12].

The specimen used in this Rapid Communication, a HIGFET, is the same as the one in Ref. [23] with a peak electron mobility of \( \sim 10 \times 10^6 \text{cm}^2 \text{V}^{-1} \text{s}^{-1} \) at the electron density of \( n = 1.5 \times 10^{11} \text{cm}^{-2} \). The magnetoresistance \( R_{xx} \) was measured by a conventional low-frequency (\( \sim 11\text{Hz} \)) lock-in technique. Different from conventional quantum Hall measurements where the magnetic field is swept, in our HIGFET specimen, the gate voltage (or electron density) is swept while the magnetic field is fixed. Details of converting gate voltage to electron density is given in the Supplemental Material Ref. [24]. This measurement setup has a few advantages. For example, with the magnetic-field constant, the
disorder configuration is fixed, and the issue associated with the magnetic-field-induced disorder potentials is alleviated. Moreover, in this constant magnetic-field setup, the separation between Landau levels is constant. Consequently the positions (in energy) of the peaks and valleys of the LLs remain unchanged as the electron density is varied. All measurements were taken at the lowest fridge base temperature of 15 mK.

Figure 1 shows $R_{xx}$ as a function of Landau-level filling factor $\nu$, which is equivalent to electron density since $\nu = n_h/eB$, at a few selected magnetic fields. Curves are shifted vertically for a better view. The oscillatory behavior in $R_{xx}$ is due to the Shubnikov–de Haas oscillations. For high Landau-level fillings (e.g., the $\nu = 16$ state) the $R_{xx}$ minima stay at the same positions as the magnetic field is varied. For lower LL filings (e.g., the $\nu = 4$ state) their minima move to a lower $\nu$ (or $n$) value as the magnetic field is reduced.

One of the challenges in observing the antilevitation behavior is to realize a highly uniform 2DES so as to ensure that a density plunging down behavior is not masked by inhomogeneity. In Fig. 2, we provide such data confirming a highly uniform 2DES has indeed been achieved in the HIGFET. In Fig. 2(a), we plot the electron density versus magnetic fields for a high Landau-level filling of $\nu = 16$. The straight line represents $n = \nu \times eB/h$. All the data points fall onto the line in the magnetic-field range of $\sim 58 - 260$ mT. To further quantify the tiny density variation in the experimental data, we subtract the theoretically expected value from the data and plot the difference as a function of the magnetic field in Fig. 2(b). It can be seen that over the experimental $B$-field range, the density difference $|\delta n|$ shows no magnetic-field dependence and is scattered between $0.1 \times 10^8$ and $-1 \times 10^8$ cm$^{-2}$ with a mean value of $\langle |\delta n| \rangle \approx -4 \times 10^7$ cm$^{-2}$. This value represents the uncertainty floor in the electron density and is much smaller than the lowest density we reached in this Rapid Communication of $\sim 8 \times 10^9$ cm$^{-2}$.

We now plot in Fig. 3(a) the electron density versus magnetic field for three low Landau-level fillings at $\nu = 4-6$. A careful examination of the data at $\nu = 4-6$ shows different $n$ versus $B$ dependences, particularly at very low magnetic fields. There, unlike the $\nu = 16$ state, the data points clearly deviate from the traditional Landau-level linear dependence and move to lower electron densities. Following the same analysis for the $\nu = 16$ state, we plot in Fig. 3(b) the difference between the experimental value and the theoretically expected one for $\nu = 4-6$. For all three fillings, the density plunges down as $B$ is reduced and $|\delta n|$ increases linearly with decreasing $B$. At $B \sim 0.1$ T, the difference reaches a value of $4 \times 10^8$ cm$^{-2}$, ten times larger than the density uncertainty floor of $4 \times 10^7$ cm$^{-2}$. In other words, an antilevitation behavior has been observed for the $\nu = 4-6$ integer quantum Hall states at very low
magnetic fields. The same antilevitation behavior has also been confirmed in another HIGFET cut from a different wafer. Details are given in Ref. [24]. This observation of antilevitation is consistent with the recent numerical simulations [12–14].

In Fig. 4, we plot $\Delta n/n$ as a function of magnetic field for two Landau-level filling factors $\nu = 16$ and 6. It can be clearly seen that for the $\nu = 16$ state where no antilevitation behavior was observed, $\Delta n/n \approx 0\%$ and is independent of the magnetic field. In contrast, for the $\nu = 6$ state where an antilevitation behavior was observed, the absolute value of $\Delta n/n$ increases with decreasing magnetic field, reaching a value of $\Delta n/n = -5.5\%$ at $B \approx 0.06$ T.

Ideally, we would like to use the peaks in the longitudinal conductivity to track the position of the delocalized states. However, in our high mobility HIGFET, due to the developing features of the fractional quantum Hall effect, for example, between $\nu = 3$ and 4 in Fig. 1, determining the positions of the conductivity (or resistivity/resistance) peaks is unreliable. On the other hand, since the magnetic field is constant in our measurements, the positions of the peaks and valleys in the LL spectrum are fixed in energy. Consequently, the valleys, or the positions of the magnetoresistance minima, can be viewed as the states (in energy) the most far away from the extended states. In this regard, using the position of a resistance minimum to track the delocalized states of a LL is justified.

The antilevitation in electron density as $B \to 0$ is surprising. In fact, a floating up in density can be expected due to a large Landau-level mixing effect [9,25,26] in the weak-field limit, even though there is no levitation in energy [9]. In the HIGFET, the Landau-level mixing parameter $\kappa = e^2/\pi l_B/\hbar\omega_c$ is over 10 at $B = 58$ mT, much larger than the $\kappa$ achieved in Ref. [15], where $l_B = (\hbar e/B)^{1/2}$ is the magnetic length, $\omega_c = eB/m^*\hbar$ is the cyclotron frequency, and $m^*$ is the effective mass of 2D electrons in GaAs. All other parameters have their normal meanings. In this regard, the observation of a plunging down in density is truly remarkable. This further attests the highest quality of the HIGFET in which an extremely weak-field regime can be achieved to reveal the antilevitation behavior.

It is interesting to notice that the antilevitation behavior is quantitatively different between the odd and the even Landau-level fillings. For example, for the $\nu = 5$ state, the initial magnetic field at which the antilevitation behavior starts to develop apparently is higher than that at $\nu = 4$ and 6. At the same time, its density plunging rate is lower. We believe that this difference between the even and the odd filling factors is due to a different origin in their energy gaps. For the even filling factor states, the gap is a cyclotron gap. For the odd LL filling factors, the gap is due to Zeeman splitting. It is known that the exchange interactions are important for Zeeman splitting enhancement at small odd fillings. Considering these, our data in Fig. 3 indicate that the exchange interactions, which have not been considered in the tight-binding numerical calculations, must play a role in the antilevitation behavior. Finally, we note that the $\nu = 4$ and 6 states show more or less the same antilevitation behavior.

Two remarks are in order before we conclude this Rapid Communication. First, we point out that the corrections due to the quantum capacitance [27] and gate depletion capacitance are small and cannot account for the observed antilevitation behavior at a vanishing magnetic field. Indeed, the geometric capacitance, which can be deduced from the electron density versus $V_g$ relation [24], is small, and $C_g = 18.2$ nF/cm$^2$. The quantum capacitance of 2D electrons in GaAs, on the other hand, is large, and $C_q = e^2/m^*/(\pi \hbar^2) = 4.5$ nF/cm$^2$. Consequently, the correction due to the quantum capacitance $\Delta n/n \approx -C_g/C_q = -0.4\%$, more than one order of magnitude smaller than $\Delta n/n = -5.5\%$ at $B \sim 0.06$ T (Fig. 4). As for the gate depletion capacitance in our HIGFET device structure, the gate depletion layer thickness is $\sim 0.6$ nm at $V_g = 1$ V (or $n \sim 1 \times 10^{11}$ cm$^{-2}$) and becomes smaller at lower gate voltages. As a result, the correction due to the gate depletion capacitance is less than 0.1% in our studied density range, again much smaller than the value of 5.5%.

Second, we note that the character of the disorder present in our HIGFET cannot account for the observed antilevitation behavior either. As shown in our early study [23], the dominant disorder in the low-density regime is the remote impurities in the heavily silicon-doped top GaAs layer, which are random and attractive. The effect of these Coulomb scatters has been shown to shift the center of the Hall plateau (or the position of the $R_{xx}$ minimum) to a lower magnetic field (or higher Landau-level filling) [28], opposite from what we observed.

To summarize, an antilevitation behavior of the Landau levels in vanishing magnetic fields was observed in a high quality heterojunction insulated-gated field-effect transistor, consistent with recent numerical calculations. Moreover, the even and odd filling factor states show quantitatively different behaviors, suggesting that the exchange interactions may play an important role in antilevitation.

We thank X. R. Wang and K. Yang for very helpful discussions. This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. Sandia National Laboratories is a multiprogram laboratory managed and operated by...
the Sandia Corporation, a wholly owned subsidiary of the Lockheed Martin Corporation, for the US Department of Energy’s National Nuclear Security Administration under Contract No. DE-AC04-94AL85000. Sample growth at Princeton was funded by the Gordon and Betty Moore Foundation through the EPiQS initiative Grant No. GBMF4420 and by the National Science Foundation MRSEC Grant No. DMR-1420541.