Magnetotransport Study of the Canted Antiferromagnetic Phase in Bilayer $\nu = 2$ Quantum Hall State

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Magnetotransport properties are investigated in the bilayer quantum Hall state at the total filling factor $\nu = 2$. We measured the activation energy elaborately as a function of the total electron density and the density difference between the two layers. Our experimental data demonstrate clearly the emergence of the canted antiferromagnetic (CAF) phase between the ferromagnetic phase and the spin-singlet phase. The stability of the CAF phase is discussed by the comparison between experimental results and theoretical calculations using a Hartree-Fock approximation and an exact diagonalization study. The data reveal also an intrinsic structure of the CAF phase divided into two regions according to the dominance between the intralayer and interlayer correlations.

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I. INTRODUCTION

Two-dimensional electron gas provides us with a simplest low-dimensional condensed matter system having the spin degree of freedom. It has a conceptual link to the unconventional superconductivities\cite{1}, Bose-Einstein condensation in two dimensions\cite{2,3} and superfluidity of $^3$He film\cite{4}. However, more fascinating phenomena are anticipated by introducing an additional degree of freedom to the two-dimensional electron systems.

In the last decade, many efforts were devoted to study bilayer quantum Hall (QH) systems\cite{5,6}, which have an additional layer degree of freedom associated with the third dimension. The layer degree of freedom is regarded as a virtual one-half spin system and named ‘pseudospin’. Although the total filling factor $\nu = 1$ QH system has only one phase without in-plane magnetic field, the $\nu = 2$ QH system has a variety of quantum phases related to a combination of the spin and the pseudospin. At $\nu = 2$, in a naive one-body picture, a phase transition occurs because of the competition between the tunneling energy $\Delta_{SAS}$ and the Zeeman energy $\Delta_Z$.

As a result, two phases occur: one is the spin-ferromagnet and pseudospin-singlet phase (F phase) for $\Delta_{SAS} < \Delta_Z$ and the other is the spin-singlet and pseudospin-ferromagnet phase (S phase) for $\Delta_{SAS} > \Delta_Z$. The F phase consists of two single-layer $\nu = 1$ QH systems. The S phase has an interlayer phase coherence due to the interlayer Coulomb interaction. Between these two phases, a novel canted antiferromagnet phase (CAF phase) has been argued to emerge\cite{7,8}.

The first experimental indication of a new phase in the $\nu = 2$ bilayer QH system was given by inelastic light scattering spectroscopy by Pelligrini et al.\cite{9}. They also observed mode softening signals indicating second-order phase transitions\cite{10}. The new phase was theoretically identified as the CAF phase by Das Sarma et al.\cite{7,8}.

This paper is organized as follows. In Section II our experimental setup is described. In Section III we report the results of elaborate magnetotransport experiments performed to quest for essential features of the CAF phase. Activation energy measurements as a function of $n_T$ and $\sigma$ show clearly that there exist three phases to be identified as the F, S and CAF phases. In Section IV we present the phase diagram in the $\sigma - n_T$ plane. We have demonstrated that the layer density imbalance causes new quantum states, i.e. two regions in the CAF phase, which have never been predicted theoretically. We also try to figure out the intrinsic spin and pseudospin structures of new regions. In Section V the phase diagram of the $\nu = 2$ bilayer QH system in the $n_T - \Delta_{SAS}$ plane is presented. Theoretical considerations by the HF approximation and the ED study are made. The ED analysis gives a quantitative support to the emergence of the CAF phase. In Section VI, we comment on the comparison between our results and several other theoretical studies.

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theoretical works.

II. EXPERIMENTS

We used a sample consisting of two GaAs quantum wells of 20 nm in width separated by a 3.1 nm-thick Al$_{0.33}$Ga$_{0.67}$As barrier. The sample was grown by molecular-beam epitaxy. Si-modulation doping is carried out only on the front side of the double-quantum-well (DQW) structure and electrons in the back side of the DQW is fully field-induced by applying a positive bias to the underlying n$^+$-GaAs gate [23]. The tunneling energy $\Delta_{SAS}$ is 11 K, the layer separation $d$ is 23.1 nm, and the low temperature mobility at $n_T = 1 \, T \, \Omega \, \text{cm}^2 \text{V}^{-1}$ is 1 $\Omega^{-1} \, \text{cm}^2 \text{V}^{-1} \text{s}$. We can control $n_T$ up to $3 \, T \, 10^{11} \, \text{cm}^{-2}$ and the density imbalance parameter $\sigma$ from 0 at the balanced configuration to 1 at the monolayer configuration continuously by applying the front- and back-gate voltages. The density imbalance parameter is defined by $\sigma = n_L - n_R = n_L - n_R$, where $n_L$ ($n_R$) is the electron density in the front (back) layer. To measure resistances, standard low-frequency ac lock-in techniques were used with a current of 20 nA and a frequency of 16.6 Hz. Throughout measurements, magnetic field is applied perpendicular to the two-dimensional plane.

III. ACTIVATION ENERGY MEASUREMENTS

First, we investigate the bilayer $\nu = 2$ QH states in the balanced density configuration ($\sigma = 0$). Figure 1 shows $R_{xx}$ as a function of the magnetic field $B$ and $n_T$, where $n_T$ is scanned while keeping $n_f = n_b$. Dark regions represent smaller $R_{xx}$ and thus QH states. The central black region around the white dashed line running from lower left to upper right in the figure indicates the $\nu = 2$ QH state. The width of the black region is related to the stability of the QH state. With increasing $n_T$, the width increases to the point indicated by the dashed arrow in Fig. 1 and decreases to the one indicated by the solid arrow, and increases again. This implies that the $\nu = 2$ QH state becomes stable, then less stable and stable again as a function of $n_T$.

To clarify this fact more, we measured the $n_T$ dependence of the activation energy $\Delta$, which was determined from the slope of the Arrehnius plot of the longitudinal resistance $R_{xx}$. $R_{xx} = R_0 \exp \left( \frac{\Delta}{k_B T} \right)$, where $T$ is the temperature. Figure 2 shows the activation energy as a function of $n_T$ in the balanced configuration ($\sigma = 0$). In the beginning, $\Delta$ gradually increases for the increment of $n_T$ from 0.6 to 10$^{11} \, \text{cm}^{-2}$ to 1 to 10$^{11} \, \text{cm}^{-2}$. After crossing the maximum, $\Delta$ decreases to the minimum at $n_T = 2 \, 10^{11} \, \text{cm}^{-2}$. Finally, $\Delta$ steeply increases after crossing the minimum point. This figure indicates that there are, at least, three phases in the balanced configuration in the $\nu = 2$ QH state. We named them the phases I, II and III from the low $n_T$ to high $n_T$ region as in Fig. 2. According to a number of theories mentioned above, the phases I, II and III should correspond to the S, CAF and F phases, respectively. It should be noted that $\Delta$ changes smoothly from the region I to II, and from II to III. This indicates that both phase transitions are not first order, as agrees well with the theoretical results [7,8,17]. It is also consistent with the light-scattering experimental result [10]. Although the exact phase transition point is not clear because of the smooth change, it would exist around $n_T$ that gives the local maximum or minimum, probably in the range shown as the two-headed arrows in Fig. 2. Hereafter we adopt the point that gives the local maximum or minimum of $\Delta$ as a representative phase transition point.

To confirm the identification of these three phases at $\sigma = 0$,
we also investigated the stability of the $v = 2$ QH states against the layer density imbalance $\sigma$ through the magneto-transport measurements in Fig. 3. We present image plots of the magnetoresistance $R_{xx}$ by changing the magnetic field $B$ and the layer density imbalance $\sigma$. The black region represents the well-developed $v = 2$ QH states. We display three typical patterns of $R_{xx}$ for three values of $n_T$. We remark the following characteristic features of the pattern as $\sigma$ is increased: (a) At $n_T = 0 \times 10^{11} \text{ cm}^{-2}$ (region I at $\sigma = 0$), the width of the stable region is almost constant; (b) At $n_T = 1 \times 10^{11} \text{ cm}^{-2}$ (region II at $\sigma = 0$), it becomes narrower and then wider slightly; (c) At $n_T = 2 \times 10^{11} \text{ cm}^{-2}$ (region III at $\sigma = 0$), it becomes narrower and then wider drastically.

To investigate the stability of these three phases against the density imbalance further, in a similar way we did for $n_T$, we also carried out the activation energy measurements as a function of $\sigma$. Results in each region are shown in Fig. 4. Although the identification of the phase at large density imbalance is important, about which we will discuss later, here we focus on the properties in the vicinity of $\sigma = 0$. In the phase I, the activation energy $\Delta$ is almost constant or gradually increases as $\sigma$ is increased. It indicates that the phase I at $\sigma = 0$ is robust against the density imbalance. This fact supports that the phase I corresponds to the S phase because the S phase is stabilized by the interlayer correlation. On the other hand, in the phase III near $\sigma = 0$, $\Delta$ steeply decreases for the initial increment of $\sigma$. It indicates that the phase III at $\sigma = 0$ is feeble against the density imbalance. This fact points out that the phase III accords to the F phase because the F phase consists of two single-layer $v = 1$ QH states. In the phase II, $\Delta$ slightly decreases or is almost constant for small density imbalance. Taking account of the dependence of $\Delta$ on $n_T$ and $\sigma$, the phase II is concluded to have properties quite different from the phases I and III.

IV. PHASE DIAGRAM IN THE $\sigma$ $n_T$ PLANE

We next construct the phase diagram in the $\sigma$-$n_T$ plane [Fig. 5(b)]. At $\sigma = 0$ the CAF-F (S-CAF) phase boundary is given by the local minimum (maximum) of $\Delta$ in Fig. 2. We made similar measurements at various values of $\sigma$. Several data are displayed in Fig. 5(a). As $\sigma$ is increased, the $n_T$ that gives the maximum of $\Delta$, the S-CAF phase boundary, stays almost constant when $\sigma < 0$ and then moves towards the larger $n_T$ side when $\sigma > 0$. On the other hand, the point that gives the minimum of $\Delta$, the CAF-F phase boundary, shifts to larger $n_T$ for small increase in $\sigma$, and disappear when $\sigma > 0$.
We plot the set of these values ($\sigma, n_T$) as open triangles (circles) in Fig. 5(b), which gives the CAF-F (S-CAF) phase boundary.

It is found that the experimentally determined F region has a finite width in $\sigma$. According to a theoretical work\cite{11}, however, the F phase is only stable just at the balanced point for the ideal case without impurities. The origin of this discrepancy can be attributed to an impurity effect. In the F phase, the $\nu = 1$ QH states are formed in both front and back layers. Once impurities broaden the plateau width for each layer, the F phase appears in the overlap region of two $\nu = 1$ QH states even if the density imbalance is made between the two layers. This is illustrated in Fig. 6.

We continue to analyze the phase diagram in the $\sigma$-$n_T$ plane [Fig. 5(b)]. We now focus on the minimum of $\Delta$ in Fig. 4. We extract a set of values ($\sigma, n_T$) that gives the minimum of $\Delta$, which are drawn as open diamonds in the phase diagram. It is interesting that the boundary (open diamonds) does not coincide either with the CAF-F boundary or the CAF-S boundary. It means that there exist two regions shown as II and IV in the CAF phase. The II-IV boundary seems to be smoothly extrapolated to the I-II boundary point at $\sigma = 0$ (dashed line) because no minimum was found at $n_T = 1 \times 10^{11}$ cm$^{-2}$ in Fig. 4(a).

The identification of the regions II and IV is intriguing. The characteristic features of the activation energy $\Delta$ are summarized as follows: As the density imbalance increases, $\Delta$ decreases in the region II just like in the F phase, while $\Delta$ increases in the region IV just as in the S phase. Recall that the intralayer (interlayer) interaction destabilizes (stabilizes) the QH system against the density imbalance. Besides the CAF phase emerges by the interplay between the spin and pseudospin interactions, that is to say, between intralayer and interlayer interactions. Since it is natural that the behavior of the activation energy is mainly controlled by the dominant interaction, the intralayer (interlayer) interaction is dominant in the region II (IV). Hence we call the regions II and IV the F-like CAF (FCAF) and the S-like CAF (SCAF), respectively. The experimentally found II-IV region boundary in Fig. 5(b)
FIG. 7: Phase diagram in the \( n_T-\Delta_{\text{SAS}} \) plane at the balanced point. The solid and open circles are the S(I)-CAF(II) and CAF(II)-F(III) phase transition points derived from the data in Fig. 3, respectively. The open square is a re-interpreted S-CAF phase boundary, while the solid and open circles are the SCAF-FCAF region boundary appeared in Ref. 21. See details in the text. The dotted line and dashed line are the calculated SCAF and CAF-F phase boundaries by the Hartree-Fock approximation. Open triangles and solid triangles are the calculated SCAF and CAF-F phase boundary points by an exact diagonalization method. Inset: Convergency of the ED method. The total density \( n_T \) at the CAF-F transition point vs. the number of electrons to be diagonalized for \( \Delta_{\text{SAS}} = 11 \text{ K} \).

must represent the balanced point between the interlayer and intralayer correlations in the two dimensional electron systems.

The structure of the spin and pseudospin has been calculated in each phase [17], which is illustrated in Fig. 5b). The magnitude of the total spin \( \mathbf{S} \) (the pseudospin \( \mathbf{P} \)) is maximal in the F phase (S phase), decreases in the CAF phase and finally vanishes in the S phase (F phase). It is well known [7, 8] that the spins are canted and make an antiferromagnetic correlation between the two layers in the CAF phase. The II-IV region boundary would be given when the ratio \( \mathbf{S} \cdot \mathbf{P} \) takes a certain critical value depending on the tunneling and Zeeman gaps, though its theoretical understanding is yet to be explored. We summarize various properties of each region in Table. 1.

V. PHASE DIAGRAM IN THE \( n_T-\Delta_{\text{SAS}} \) PLANE

Finally we construct the phase diagram in the \( n_T-\Delta_{\text{SAS}} \) plane. The theoretical SCAF phase boundary is calculated by the HF approximation from the equation: [8, 15, 17]

\[
\Delta_Z = \frac{P}{\Delta_{\text{SAS}} \varphi_{\text{SAS}} E_C / t}
\]

where \( E_C \) is the capacitance energy between two layers. In the same way, the CAF-F phase boundary is determined from the equation:

\[
\Delta_Z = \frac{\Delta_{\text{SAS}}^2 + E_C / 2}{E_C / 2}
\]

They are shown in Fig. 7 by the dotted and dashed lines, respectively. However, an ED study has suggested [14] that the S-CAF phase boundary in the HF approximation is not reliable. We carried out an ED analysis of the phase diagram in the \( n_T-\Delta_{\text{SAS}} \) plane, whose results are plotted as open triangles with solid lines in the same figure. The convergency for the CAF-F phase boundary is quite good for more than 6 particles to be diagonalized. On the other hand, calculated points on the S-CAF boundary converge only gradually against the number of particles \( N \) (see the inset in Fig. 7). We display the asymptotic values for \( N! \sim \infty \) in Fig. 7. The agreement of the CAF-F boundary between the HF approximation and the ED analysis is extremely good. This is because the HF result is exact for the CAF-F boundary [17].

We mark the \( n_T-\Delta_{\text{SAS}} \) phase diagram (Fig. 7) with open and solid circles representing the present experimental results. The agreement of our experimental data points with the ED analysis is reasonably well but not perfect. The disagreement would be due to the finite width of quantum wells, which is neglected in theoretical calculations but is known to modify the Coulomb energy considerably.

Here we review the experimental data given in Ref. 19, where a sample with \( \Delta_{\text{SAS}} = 6.7 \text{ K} \) was used. In view of our present understanding, the phase transition point at \( n_T = 0.9 \times 10^{11} \text{ cm}^{-2} \) in Fig. 4 of this reference is interpreted as the CAF-F phase boundary. On the other hand, there is no definite data for the S-CAF phase boundary. Nevertheless, Fig. 3 of this reference tells us that the QH state at \( n_T = 0.6 \times 10^{11} \text{ cm}^{-2} \) is in the S phase. Hence, the S-CAF phase boundary must be between \( 0.6 \times 10^{11} \text{ cm}^{-2} \) and \( 0.9 \times 10^{11} \text{ cm}^{-2} \). We plot these points as squares in Fig. 7. We also re-analyzed the data based on Hall-plateau width measurements in Ref. 21. Though they did not find any phase transition points at \( \sigma = 0 \) for two samples with \( \Delta_{\text{SAS}} = 1 \text{ K} \) and \( \Delta_{\text{SAS}} = 23 \text{ K} \), they did for two other samples with \( \Delta_{\text{SAS}} = 4 \text{ K} \) and \( \Delta_{\text{SAS}} = 11 \text{ K} \). They identified the point that gives the minimum of the Hall plateau width for \( \sigma \) at the fixed \( n_T \) as the F-S phase transition point. However, from our current understanding, the point which gives the minimum of \( \Delta \) against \( \sigma \) should be interpreted as the SCAF-FCAF phase boundary. This point is re-interpreted as the SCAF (S-FCAF) phase transition point due to the fact that the SCAF region seems to vanish at \( \sigma = 0 \) in the present work. We also plot these two points as solid diamonds in Fig. 7. The SCAF phase boundary of the current data is slightly different from the one determined from Ref. 21. One reason of this discrepancy of the S-CAF phase boundary is the method to determine the phase boundary. To analyze the S-CAF phase transition point in Ref. 21, we need the assumption that the SCAF phase vanishes at \( \sigma = 0 \), and thus the FCAF-SCAF phase boundary coincides to the S-FCAF phase boundary. Another possibility is different measuring methods. Though the Hall
plateau width measurements and the activation energy measurements present qualitatively similar results, there is no reason that these two results are identical. The activation energy measurement is more reliable.

VI. COMMENTS

Carrying out elaborate magnetotransport measurements, we have established the existence of three phases in the $\nu = 2$ bilayer QH system. Our new finding is an intrinsic structure of the CAF phase represented by the FCAF and SCAF regions in the imbalanced density configuration.

We make comments on related theoretical works. Brey et al. predicted that there arise new coherent phases for large layer density imbalance[16]. For large bias voltage the CAF phase would become the coherent canted (CC) phase. However this CC phase is only stable at zero tunneling limit $\Delta S_{0} = 0$. Since our sample has a large tunneling energy, it is difficult to identify the region IV as the CC phase. Demler et al. suggested that there exist the Bose-glass phase due to nonzero disorder effect[11]. Though their theoretical calculation was performed only in the balanced density configuration, it would be worthwhile to try to identify the region II (IV) with a Bose-glass phase made of domains of the CAF phase surrounded by domains of the F (S) phase. However, a theoretical study of the Bose-glass phase in the imbalanced configuration will be indispensable for further discussions.

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