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Composite Fermion States around 2D Hole Landau Level Filling Factor 3/2 in Tilted Magnetic Fields

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Abstract

Transport measurements under tilted magnetic fields were performed on a series of C-doped (001) GaAs/AlGaAs two-dimensional hole quantum wells. Due to a large *g*-factor, Zeeman energy is large and comparable to the cyclotron energy in these samples. On the other hand, it was found that the in-plane component $g_{//}$ is small, and the effect of a tilted magnetic field is mainly to increase the effective mass of holes. We investigate the spin transition of composite fermion states around Landau level (LL) filling factor 3/2. We found that the ν = 4/3 state encounters a partial- to full- spin polarization transition, conforming to the same pattern as that of electron samples. In addition, a high-resistance phase emerges at ν = 3/2 under very high tilt angles. We interpret both of these phenomena as a consequence of LL crossing under a purely perpendicular magnetic field.

I. INTRODUCTION

The composite fermion (CF) model[1,2] has made a great success in descripting the fractional quantum Hall effect (FQHE), especially for $p/(2p \pm 1)$ series around half-filling of the lowest Landau level (LL). In this model, a CF is formed by attaching 2 magnetic flux quanta to an electron. The attached fluxes, so called Chern-Simons fluxes, cancel the applied magnetic field and make the mean field felt by CFs zero at corresponding even-denominator filling factor ν = 1/2. The problem of FQHE then reduces to CF's integer quantum Hall effect. Experiments have confirmed CFs with an effective mass[3,4], a well-defined Fermi vector, and consequently, a semi-classic motion[5,6]. Angular dependent magneto-transport measurement provides a way to investigate the LL spectrum of CFs, or Λ-Level (ΛL). A tilt magnetic field is applied in this type of measurement. In ideal two-dimensional systems, only the perpendicular component of the magnetic field contributes to E_C, the cyclotron energy, while the total field contributes to E_Z, the Zeeman energy. This is true for GaAs two-dimensional electron gas (2DEG). By changing the tilt angle, we change the ratio between E_c and E_z and get information about the LL for electrons as well as the ΛL for CFs. GaAs two-dimensional hole gas (2DHG) behaves differently from ideal 2D systems. Holes has a non-zero total angular momentum of 3/2. Heavy-hole (HH) light-hole (LH) splitting enforces the quantization axis of holes' angular momentum to point perpendicular to the quasi 2D plane. The quantization axis can't be easily changed by an in-plane magnetic field so that Zeeman splitting in an in-plane magnetic field is a higher-order effect. The in-plane g-factor is so small in 2DHG that its E_z is determined mainly by the perpendicular component of magnetic fields[10]. However, in-plane magnetic fields would increase the effective mass of holes, consequently leads to a relative decrease of E_c to E_z. It has been revealed by this method that around ν = 3/2 in GaAs 2DEG, a) CF has a g-factor largely the same as that of the underlying electrons, b) ν and $2-\nu$ FQH states are counterparts with the same ΛL filling factor[7]. The g-factor in 2DEG is very small (-0.44), resulting in a zero-tilt Zeeman energy that is about 1/60 of E_c. Whether these spin-related properties of CFs would still hold for systems with larger g-factors, especially ones with Zeeman energy comparable to or even larger than cyclotron energy remains an open question.

In GaAs materials, 2DHG has a g-factor larger than 2DEG. The latter has a small g-factor of only -0.44[8]. In 2DHG, the theoretical predicted $g_{\perp}$ value is 7.2[9, 10]. The measured value of g-factor is usually obtained by optical method and smaller than theoretical value[11-13]. In early transport studies, a high-quality 2DHG is obtained by Si doping on (113) GaAs substrate. There are several works investigating FQH states around ν = 3/2 on (113) GaAs 2DHG, reporting very similar behavior to those in 2DEG[14-16]. The g-factor in relevant analysis is not large (1.1 ~1.2). 2DHG in C-doped (001) GaAs provides another alternative[17, 18]. Due to the p-like symmetry of valance band, hole's g-factor is orientation dependent. It is reported that the effective g-factor in C-doped (001) 2DHG is large enough to cause LL crossing around 1T, with the magnetic field solely perpendicular to the sample plane[19]. (001) GaAs substrate provides higher symmetry than (113), hence more isotropic in-plane mobility and g-factor,[10, 12] and less heavy-hole light-hole mixing[20]. It also provides a basis for the comparison of high mobility 2DHG and 2DEG in the same crystallographic growth direction. Here we perform angular dependent magneto-transport measurements on a series of MBE grown, C-doped, p-type (001) GaAs quantum well samples around hole filling factor 3/2. We found that in this system, the transition of FQH states around 3/2 is similar to that of 2DEG and (113) 2DHG at low tilt angles. At higher tilt angles, stripe phase emerges, which has not been observed in the other two systems.

II. METHOD

Four samples, denoted by A-D and covering a density range of $0.7\sim1.5*10^{11}$ cm^{-2} were measured in this study. Table I lists relevant information for each sample. All specimen are in the van der Pauw geometry, each with eight In/Zn contacts diffused symmetrically on the perimeter. The specimen was immersed into the coolants of a dilution refrigerator with a base temperature T~20mK. A rotator is mounted to facilitate the sample *in situ* rotation around an axis perpendicular to the magnetic field. Standard four-terminal lock-in technique was used in the experiment, with a measurement current of 10nA. An overview of transport traces from sample C and the experimental configuration is depicted in Fig. 1. The tilt angle θ is defined as the angle between magnetic field and normal of the 2DHG plane.

III. DATA AND DISCUSSION

When subjected to fields with increasing tilt angle θ, states around ν=3/2 in our samples exhibit two types of transition as illustrated in Fig. 2. For sample C, R_{xx} minimum and R_{xy} plateau at ν=4/3 disappear first and reappear again at larger θ. For sample D, whose carrier density is higher, the trace shows no significant change until an insulating phase (IP) emerges at large θ. The insulating phase at high tilt was observed in all four samples and will be further discussed later. A detailed plot of R_{xx} at fixed filling factor versus B_{tot} in different samples is shown in Fig. 3a. For samples A-C whose densities $p<1*10^{11}$ cm^{-2}, $R_{xx}(4/3)$ shows a peak that exceeds the value of $R_{xx}(3/2)$, at low tilt angles. The peak indicates a closing and reopening of gap at ν=4/3. $R_{xx}(5/3)$ keeps unchanged or initially drops due to gap enhancement with increasing θ. $R_{xx}(4/3)$ always exceeds $R_{xx}(5/3)$ after the former's transition, suggesting a change in their gaps' relative magnitude. The gap evolution can be easily understood in the view of CF's ΛL. Fig. 3b shows a schematic diagram of ΛL. 4/3 state has a ΛL filling factor λ=2 while 5/3 state has a ΛL filling factor λ=1. At zero tilt in sample

A-C, the spin splitting of ΛL is small. When the tilt angle increases, λ=2 state undergoes a gap closing and reopening while λ=1 state only increases its gap at the beginning. For sample D, R_{xx} of 4/3 is always larger than that of 5/3 and there is no peak in $R_{xx}(4/3)$ before the IP appears. The case in sample D suggests that even at zero tilt the splitting of ΛL is large enough that the transition has already happened. This is not unexpected. The gap of ΛL is proportional to $\sqrt{B}$ while the splitting of ΛL, which is determined by the Zeeman energy, is proportional to B. Increasing density results in increasing B for a fixed FQH state and thus increasing the relative splitting of ΛL.

One may recall previous works on 2DEG[7] and (113) GaAs 2DHG[14-16], which showed the same evolution in 4/3 and 5/3 as sample A-C. So their ΛL has the same structure, with the electron (hole) filling factor $\nu = 2 - \lambda/(2\lambda \pm 1) = (3\lambda \pm 2)/(2\lambda \pm 1)$ equivalent to a CF filling factor of λ, which was established in Ref. 7.

For the purpose of further understanding ΛL of CFs, we now trace back to the underlying LL of holes. Due to the fact that the Zeeman energy in C-doped (001) 2DHG is so large, it exceeds cyclotron energy even at zero tilt in these samples, the LL structure of (001) 2DHG is dramatically different from that of 2DEG and (113) 2DHG. It should be instructive to look at relevant energy scales here. GaAs 2DEG has a g-factor of -0.44, effective mass of 0.067, leading to a Zeeman energy E_z of 0.3K/T and cyclotron energy $\hbar\omega_c$ of 20.1K/T. For holes in Ref. 14 hosted by Si-doped (113) GaAs, the values for analysis are g =1.1 and m^*=0.38, so E_z =0.73 K/T, $\hbar\omega_c$ =3.5 K/T. Zeeman energy is small compared with cyclotron energy in both systems. However, for holes in C-doped (001) GaAs QWs, Yuan et al.[19] reported a g-factor between 5 ~ 7.2 and m^*=0.4, resulting in a Zeeman energy (3.4 ~ 4.8 K/T) already larger than cyclotron energy (3.4 K/T) in the region $B_\perp \approx 1T$. Zero field spin splitting in 2DHG of similar parameters has an energy about 1K, which is less important at high fields.

It should be noted that in Ref. 19 the authors only analyze the LLs around $B_\perp = 1T$ with a filling factor of about 9, a density $p = 2.2*10^{11}$ cm^{-2}. The LL spectrum in 2DHG is non-linear and complicated. Even though the Zeeman energy is large, there is still a distance to getting the conclusion that, in C-doped (001) GaAs 2DHG systems, FQH states around hole filling factor 3/2 take place in $|N=1,\uparrow>$ Landau level (Fig. 4c) rather than usual $|N = 0,\downarrow>$ level (Fig. 4b). However, our data supports an inverted LL index. In the situation of Fig. 4c, one can define an effective Zeeman energy $E_z^*=|E_z-\hbar\omega_c|$ that characterizes the spin-splitting gap between the LL hosting 3/2 state and the one above it. The splitting of ΛL should be the size of E_z^* instead of E_z. Even though E_z would not increase in the case of 2DHG[19], E_z^* will increase with increasing B_{tot} at a fixed hole filling factor, inducing the spin transition of 4/3 state. A Zeeman energy slightly smaller than LL gap (Fig. 4b) may also induce a transition of 4/3 state for a similar reason, but here E_z^* decreases with increasing B_{tot}. The dropping of $R_{xx}(5/3)$ at the beginning of tilting and the fact that $R_{xx}(5/3)$ goes smaller than $R_{xx}(4/3)$ after the latter's transition (Fig. 3a) require an increasing E_z^* (thus a increasing CF splitting) with increasing B_{tot}.

The relationship between $1/\cos\theta_c$ and carrier density p (also $B_{4/3}$, the perpendicular magnetic field at ν=4/3) is illustrated in Fig. 3(c), θ_c stands for the critical θ where 4/3 state disappears. There is a roughly linear relationship between $1/\cos\theta_c$ and p although we do not have a quantitative understanding of this feature. Qualitatively, the effect of in-plane field is to decrease the effective mass (orbit effect), rather than to increase the Zeeman energy (spin effect), despite both result in increasing the relative Zeeman energy to the cyclotron energy.

At high tilt, an insulating phase becomes the ground state around 3/2, instead of FQH states (Fig. 5). This is unusual since in previous works on GaAs 2DEG and 2DHG no stripe phase is reported at filling factors between 1 and 2. In 2DEG the insulating phase, or called stripe phase, is only observed around half fillings at $\nu > 4$ ($\nu > 2$) without (with) in-plane magnetic fields[21-25].

In 2DHG, Manfra et al.[26] reported an observation of stripe phase without in-plane field at ν=7/2 while the usual one at ν = 9/2 is missing. They explained it as a consequence of LL mixing due to spin-orbit coupling. The mixing of orbitals from higher Landau levels (N = 2, 4 and 5) results in a hole-hole pseudo-potential favoring a stripe phase. Mixing is significant in 2DHG because hole's effective mass is large[27]. The crossing of LL may provide an alternative explanation. By crossing, LLs hosting 7/2 (5/2) and 9/2 (3/2) are swapped, so 7/2 state shall behave like previous 9/2, and 3/2 state shall behave like previous 5/2. The stripe phase which should arise at 9/2 and 5/2 then would arise at 7/2 (without in-plane field) and 3/2 (with in-plane field). In other words, here in the tilted fields the 3/2 retains the two-nodes N = 2 LL characteristics, behaving like half-filled high LL states. The LL crossing also exists in other 2D systems like ZnO[28] or $Cd_{1-x}Mn_xTe$[29]. In the case of ZnO, LL crossing is also the candidate scenario to explain the FQH state observed at 3/2[28].

A detail measurement of IP was performed on sample D. Fig. 6a shows strong anisotropy in the order of 1000:1, consistent with the property of stripe phase observed in 2DEG. The temperature dependence in Fig. 6c shows activated transport behavior associated with an activation energy E_g = 0.44K, in $R_{xx} \propto \exp(E_g / k_b T)$. The peak starts to 'melt' at about 100mK. It should be noted that in our samples, only a single IP appears in the region $\nu > 1$ (Fig. 6b).

IV. CONCLUSION

In conclusion, by performing angular dependent magneto-transport measurements on four C-doped p-type (001) GaAs quantum well samples, we observed spin transition of 4/3 state and found an in-plane magnetic field induced stripe phase at ν = 3/2. Although these two effects were observed at a finite tilt magnetic field, our analysis shows that the LLs crossing could occur even at zero tilt. This work provides an example of new phase such as stripe phase arising at lower LLs comparing to those commonly known in high LLs.

Recently, Liu et al. have reported similar results in 2DHG confined in wider quantum wells (30 and 35nm)[30].

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TABLE I. Sample information. All 4 samples are cleaved from MBE grown, C-doped, p-type (001) GaAs quantum well wafers. B and C are cleaved from the same wafer.

	A	B	C	D
width of QW (nm)	17.5	17.5	17.5	20
density (10^{11} cm^{-2})	0.70	0.86	0.94	1.54
mobility (10^{6} cm^{2}/Vs)	0.6	1.1	1.3	1.7
doping[a]	a	s	s	s

[a] a for one-side asymmetric doping, s for two-sides symmetric doping.

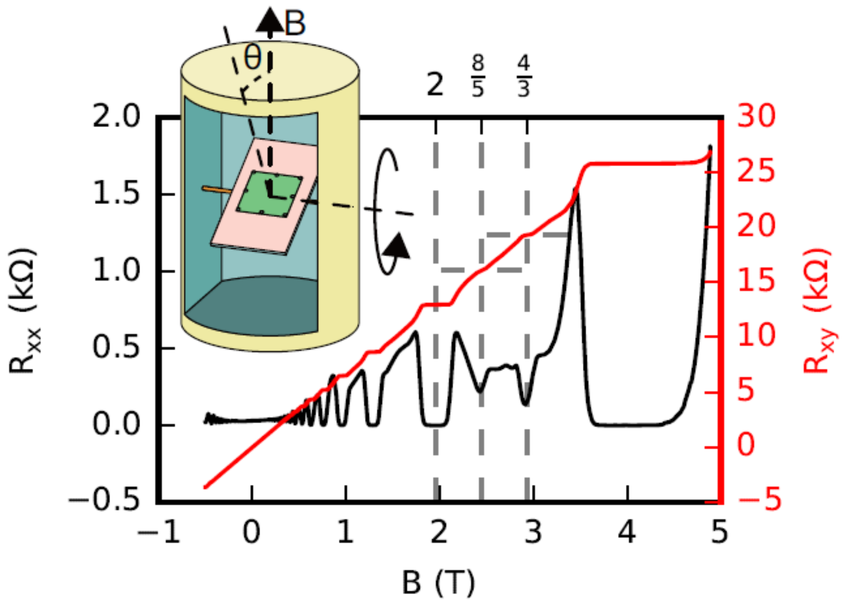

FIG. 1. Overview of R_{xx} and R_{xy} at zero tilt in sample C. A schematic diagram of experimental configuration is shown in the inset. The van der Pauw sample was mounted on a rotatable stage and immersed in the coolants of a dilution refrigerator.

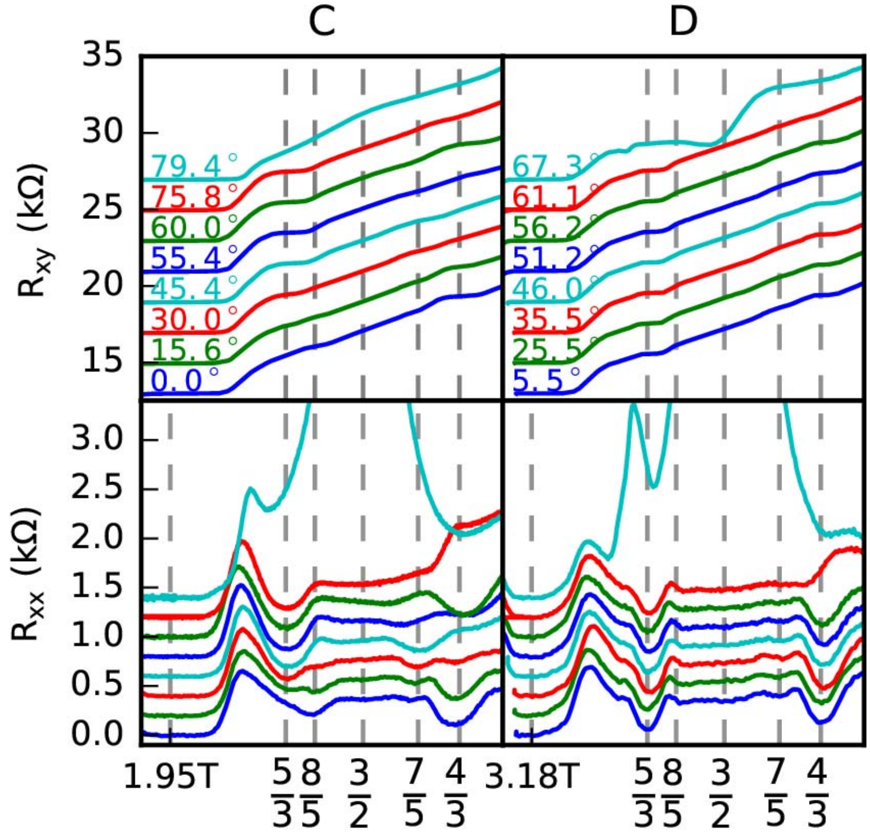

FIG. 2. Angular dependence of R_{xx} and R_{xy} in sample C and D. While sample C encounters a transition of 4/3 state as well as a gap enlargement of 5/3 state, sample D shows no significant change in these states until at higher angles insulating phases arise in both samples. Curves are shifted vertically for clarify. The values of tilt angle are marked above the R_{xy} curves. The labels on lateral axis are $B_{\perp}$ at $\nu = 2$ followed by hole filling factors.

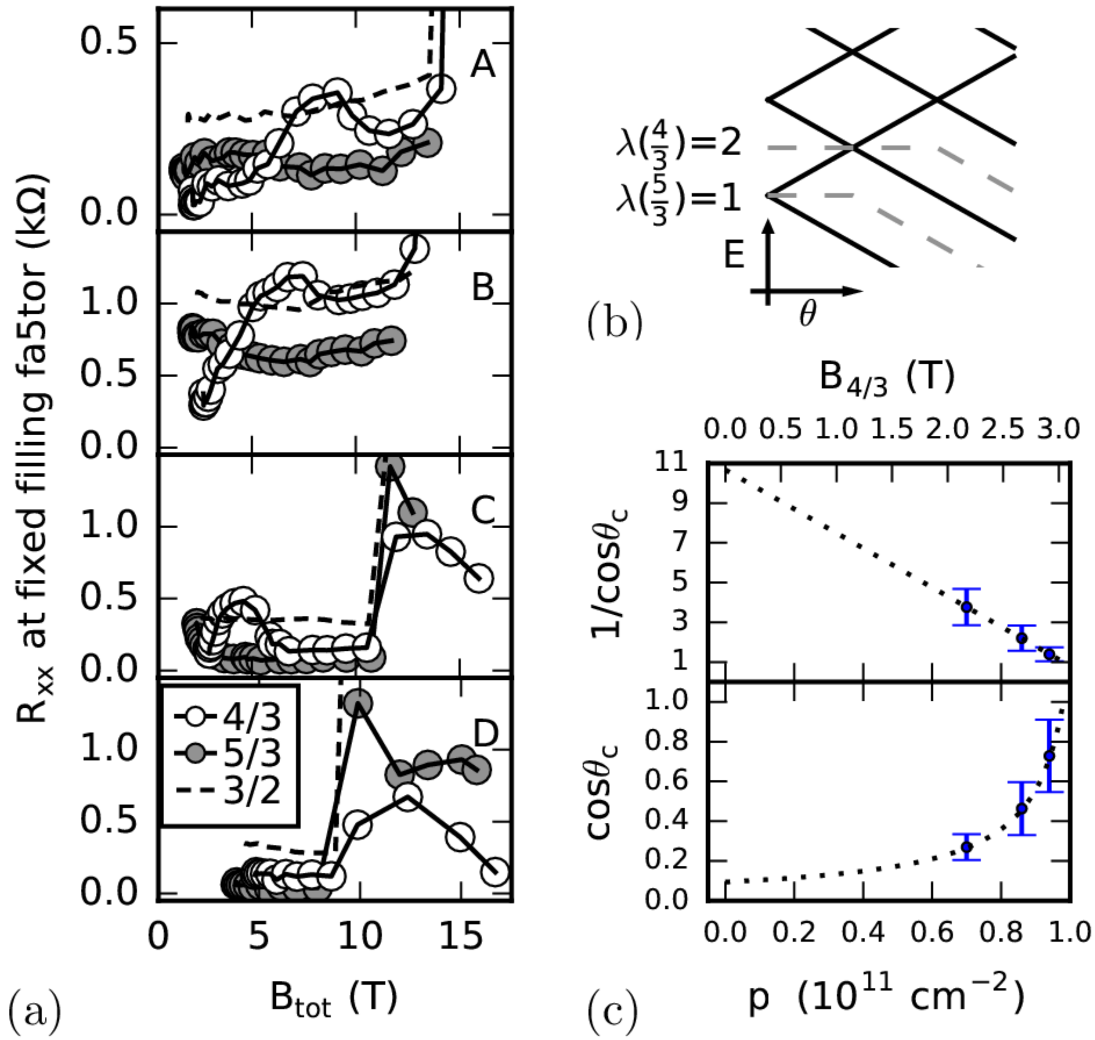

FIG. 3. (a) R_{xx} at fixed filling factor versus B_{tot} in different samples. Legend is depicted in the bottom panel. (b) A sketch of CF's *Λ-level evolution* with tilt angle θ. The energy gap of 4/3 state closes and reopens. The evolution is *not* driven by a Zeeman energy in in-plane fields since in-plane g-factor of 2DHG systems is nearly zero. Instead it is driven by the orbital effect of in-plane fields that reduces holes' effective mass. (c) $1/\cos\theta_c$ versus density p (and $B_\perp$ at $\nu = 4/3$) shows a roughly linear relationship. θ_c is the critical angle where 4/3 transition takes place. Lower limit of the error bar corresponds to the smallest θ where minimum of 4/3 state disappears in our R_{xx} vs B curves and upper limit corresponds to the largest one.

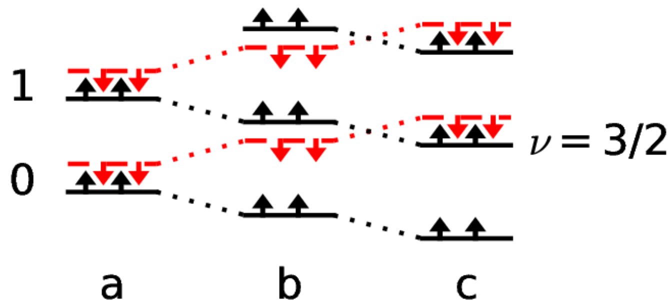

FIG. 4. Schematic of LL spectrum in systems with different g-factors at zero tilt. (a) depicts GaAs 2DEG LLs. (b) is hypothetical LLs with medium g-factor. (c) is our proposed LLs of C-doped (001) GaAs 2DHG, where LL crossing already happens at zero tilt.

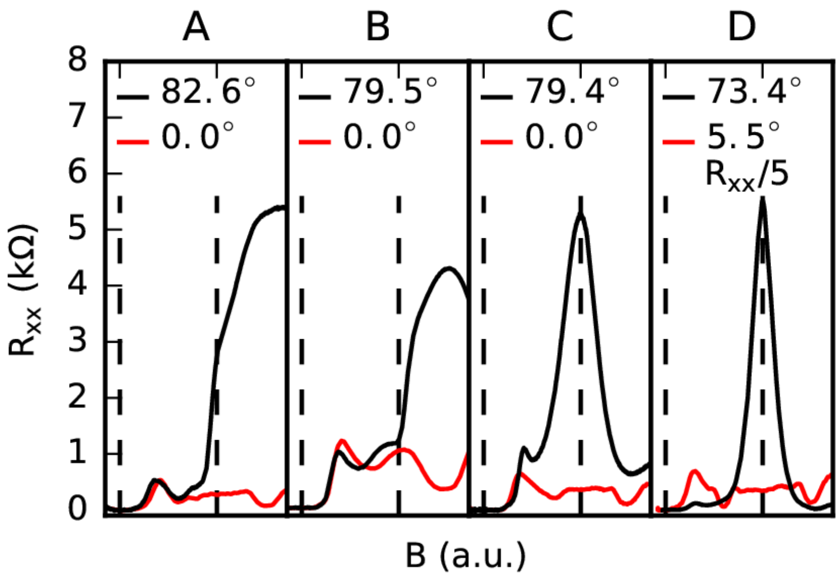

FIG. 5. An overview of insulating phase. The dashed vertical lines in each subfigure indicate fields where v = 2 (left) and 3/2 (right). The insulating phase comes up at high tilt angles in all four samples, around v = 3/2. The stripe phase in sample A and B is not fully established due to the limitation of equipment's maximum magnetic field. R_{xx} for sample D at 73.4° is divided by 5, here the 'x' in the subscript means that the current is parallel to the in-plane magnetic field.

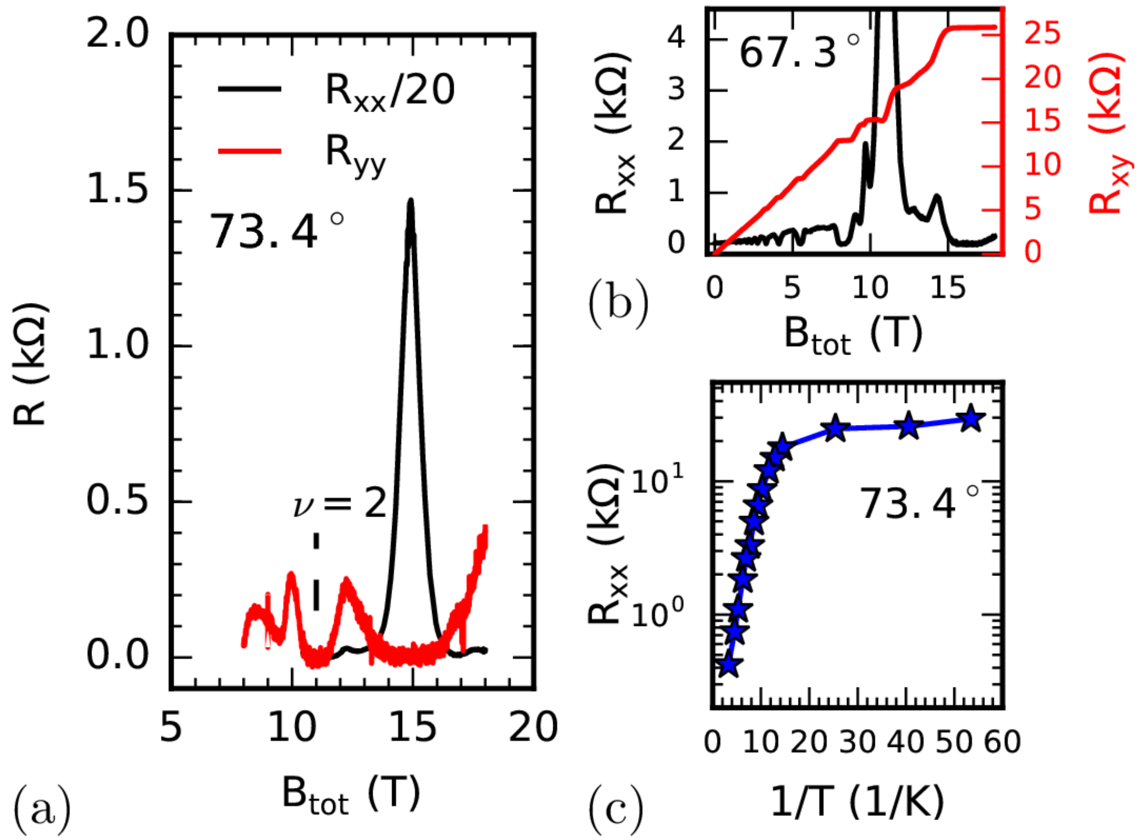

FIG. 6. Details of insulating phase (IP) in sample D. Tilt angles are noted on each panel. (a) Anisotropy between R_{xx} and R_{yy} indicates a stripe phase. 'x' in the subscript means that the current is parallel to the in-plane magnetic field while 'y' means perpendicular. (b) Unlike in 2DEG where stripe phases come up in pairs, in sample D only a single IP appears in the region $\nu > 1$. (c) Temperature dependence of IP. The linear region indicates an activation energy of 0.44K.