Formation of a chiral surface state and interlayer conduction in a bulk quantum Hall system

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Resistance measurements have been performed for the bulk quantum Hall system $(TMTSF)_2AsF_6$, where TMTSF denotes tetramethyltetraselenafulvalene. The interlayer resistance in the quantum Hall states is found to be independent of both temperature and quantum number at low temperatures. This fact can be ascribed to the formation of the chiral surface state, but the resistivity is much smaller than theoretical prediction. Sharp peaks in the interlayer resistance appear at transition fields between the adjacent quantum Hall states. The results suggest the presence of an intermediate state, which is not necessarily expected from standard theory. [S0163-1829(99)04527-0]

I. INTRODUCTION

Two-dimensional (2D) electronic systems have been extensively studied because of the observation of the quantum Hall (QH) effect. In the absence of magnetic field, all the electronic states in 2D systems are expected to be localized by disorder for $T=0$. In a weak-localization regime, the conductivity shows a logarithmic temperature dependence at low temperatures, which is described by diffusive motion of the electrons, and then drops to zero with decreasing temperature. In the presence of high magnetic field, the electronic states split into Landau levels, and bulk extended states appear when the Fermi level lies near the centers of the Landau levels. This state shows a temperature independent conductivity $\sigma_{xx}\sim e^2/h$. Away from the centers of the Landau levels, where the QH effect is observed, all the electronic states are localized within the bulk of the sample, but extended states (edge states) are present at the edge of the sample. The edge state is insensitive to scattering due to disorder because all the electrons in the edge state must propagate along one direction perpendicular to the field. One of the most interesting features for the edge states is the fact that the back scattering is necessarily prohibited in the ideal case.

Recently, theoretical studies[1,2] argued that a 2D electronic system can exist, which has diffusive conductivity much less than $\sim e^2/h$. This 2D system can be formed by stacking the edge states in the QH regime. For semiconductor multilayer systems, an integer QH state is expected to be almost independently present in each layer when the QH gap E_g $(=\hbar\omega_c)$ is larger than the transfer integral t between the layers. In this case, the surface of the sample is enveloped by a sheath of the edge states [Fig. 1(a)], and a 2D electronic state, the so-called chiral surface state, is formed on the side of the sample.[1,2] The electronic states of such layered samples in the QH state have been theoretically investigated, and the chiral surface state realized in the bulk QH systems is predicted to have significant differences from ordinary 2D electronic states.[1,2] Recently, Druist *et al.* measured the interlayer conductance of GaAs multilayers in the integer QH

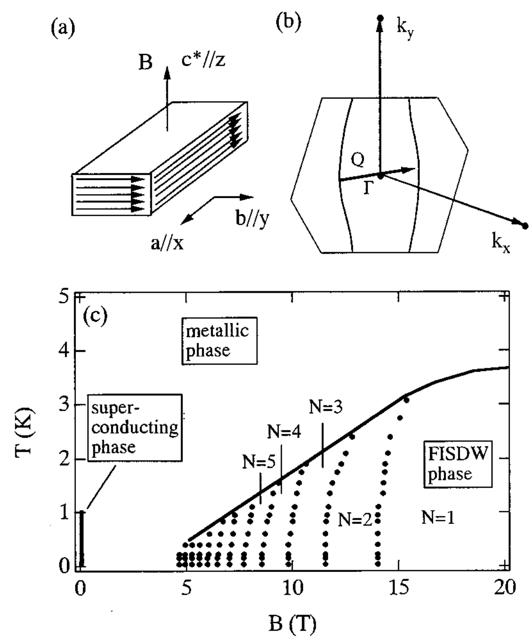

FIG. 1. (a) Geometry of a 3D quantum Hall sample. The arrows indicate the electron motion in the chiral surface state. The crystal axes for $(TMTSF)_2AsF_6$ are shown. (b) Schematic picture of two sheets of 1D Fermi surface for $(TMTSF)_2AsF_6$ based on the band calculation (Ref. 5). Q denotes the SDW nesting vector. (c) Phase diagram at 8 kbar determined by this work. N denotes the quantum number in the quantum Hall states (FISDW states).

states[3] and found that the conductance is proportional to the sample perimeter. This fact unambiguously shows that the electron transport takes place only on the side of the sample rather than through the bulk. The conductance is much less than e^2/h, which is consistent with theoretical prediction.[1,2]

On the other hand, quasi-one-dimensional organic conductors $(TMTSF)_2X$, where TMTSF denotes tetramethyltetraselenafulvalene, are known as the first bulk system showing QH effect. For $(TMTSF)_2X$ ($X = AsF_6$, PF_6, etc.), the metallic state is stabilized down to the base temperature by applying high pressures.[4] These salts have two sheets of 1D Fermi surface as shown in Fig. 1(b).[5] When the magnetic field is applied perpendicular to the conduction plane (*ab* plane), a cascade-type spin-density-wave (SDW) state is induced [Fig. 1(c)]. The systematic studies of the QH state were carried out for the PF_6 salt by two different groups.[6,7] They found that the Hall resistance is quantized in the field-induced spin-density-wave (FISDW) states in a wide field region. The overall behavior of the FISDW transitions is well understood in the framework of standard theory,[4] although a pressure-dependent irregular sequence of the transitions, so-called Ribault anomaly, is found in the Hall resistance.[8–10] The standard theory is based on the assumption that a small closed orbit is formed by an imperfect nesting of the corrugated 1D Fermi surface. The nesting vector in each FISDW state changes with magnetic field so that the Fermi level is always kept between the adjacent Landau levels. The Landau levels result from the Landau quantization of the small closed orbit. Each Landau level is always completely filled or empty in the FISDW states, which consequently enables us to observe the quantized Hall resistance in the wide field region. The formation of the edge state for the TMTSF systems is theoretically established by Yakovenko and Goan.[11] In the *N*th FISDW state, the electronic states of the N chains from the edge in each conduction plane are extended (ungapped) although the energy bands of all other chains in the bulk are gapped. These extended states at the edge form chiral surface states.

In order to investigate the nature of the chiral surface state realized in the TMTSF systems, we have performed the resistance measurements at high magnetic fields up to 16 T over a wide temperature range. A standard Cu(Be) clamp cell was used for the pressure experiments. Electrical contact to the samples was made with ϕ 10 μm gold wires and a silver paint.

II. EXPERIMENTAL RESULTS

Figure 2 presents the Hall resistance (R_{xy}) at 0.04 K. The Hall resistance is negligibly small in the metallic state but shows an upturn at the threshold field (~5 T), followed by a series of the Hall steps. These steps are observed only in the FISDW states, which are characterized by the quantum number *N*. The Hall step for the $N=1$ state is not evident as compared with the reported results.[6,7] The fact may be due to somewhat high pressure or sample inhomogeneity, causing the broadening of the Landau levels and the transition width. The *a* axis resistance R_{xx} does not completely decrease to zero in the QH states in contrast to the case of 2D electron gas in semiconductor heterostructures. In the FISDW states, the effect of impurities on the QH effect is significantly different from the conventional QH effect in 2D electron gas.[12,13] For the TMTSF systems, the impurity scattering in the sample is suggested to allow for the presence of conducting open orbits and introduce a finite density of states at the Fermi level.[12] This scattering gives rise to nonzero R_{xx} and imperfect Hall plateaus, although the sheet Hall resistance is experimentally close to the ideal values, $Nh/2e^2$,[6,9,14] where the factor 2 comes from the spin degeneracy.

Figure 3 presents the field dependence of the *c*-axis resistance R_{zz} at various temperatures. At 0.04 K, R_{zz} steeply

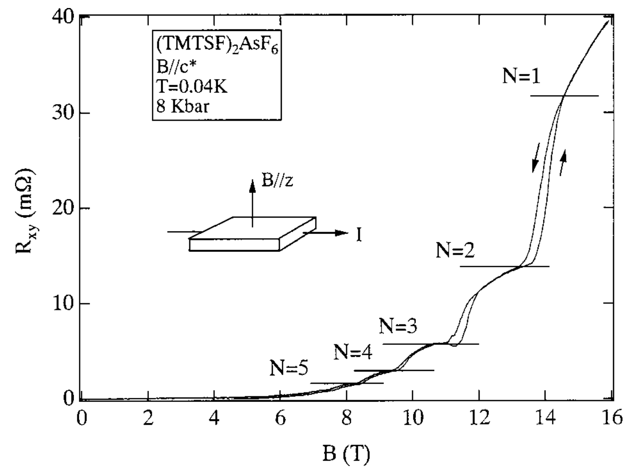

FIG. 2. Hall resistance (R_{xy}) of $(TMTSF)_2AsF_6$ at 8 kbar for $T = 0.04$ K.

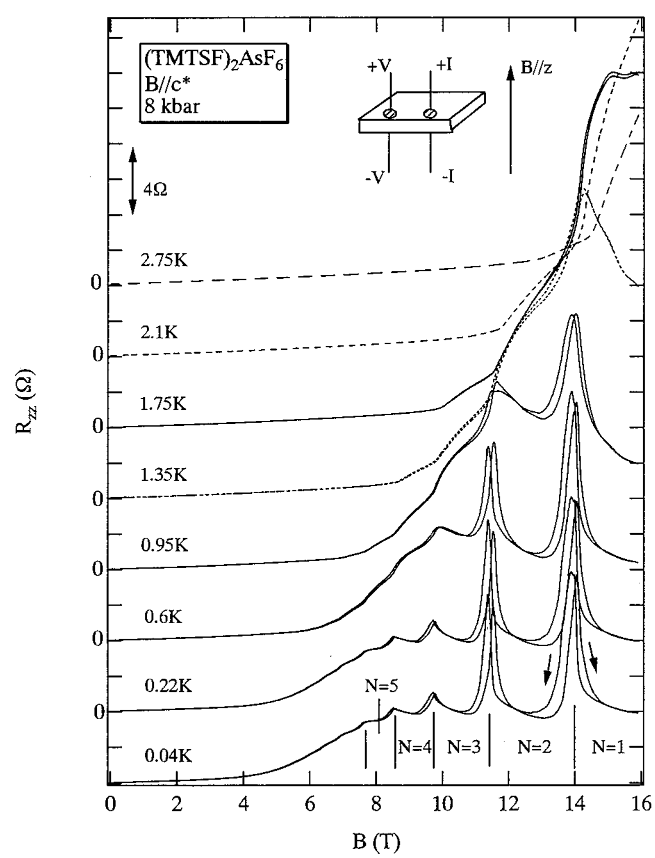

FIG. 3. Interlayer resistance (R_{zz}) at various temperatures for $(TMTSF)_2AsF_6$. The data are shifted up for clarity. The configuration of the electric contact is shown for the R_{zz} measurements.

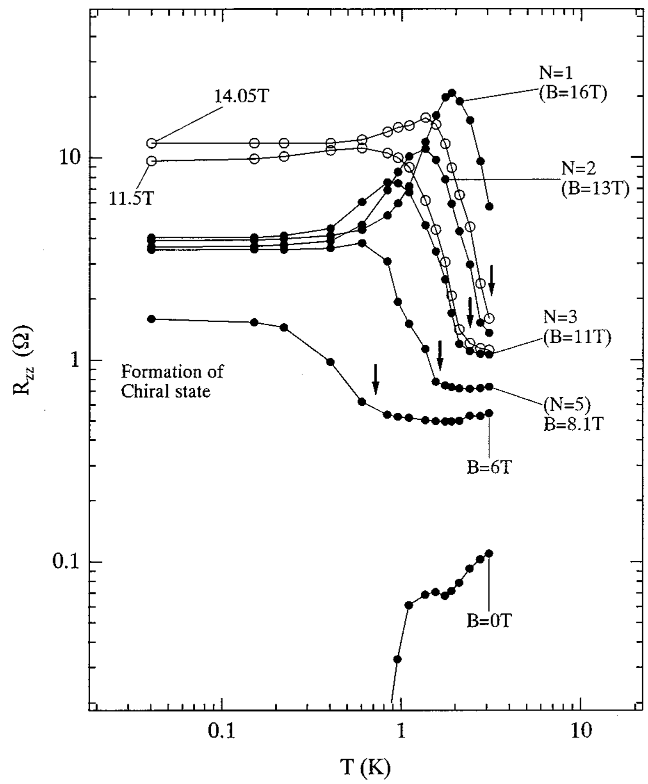

FIG. 4. Temperature dependence of the resistance R_{zz} at various magnetic fields for $(TMTSF)_2AsF_6$. Closed circles: R_{zz} in quantum Hall states for $N=1$, 2, 3 and 5, at 6 T and at zero field. Open circles: R_{zz} at the transitions from the $N=3$ to 2 state ($B=11.5$ T) and from the $N=2$ to 1 state ($B=14$ T). Arrows indicate the FISDW transition from the high-temperature metallic state.

increases above the transition field and shows a characteristic structure due to the FISDW transitions. A remarkable feature is the presence of the sharp peaks, which are seen at transitions from one QH state to another for $N<5$. The overall peak structure does not change up to 0.4 K, but the peaks become broad with increasing temperature above 0.4 K. At 2.1 K, the peaks are completely smeared out and only kinks are observable.

The above results are completely different from those observed for the GaAs multilayers.[3] For the GaAs multilayers, the in-plane resistance decreases down to zero in the QH states, showing the localization in the bulk of the sample, i.e., no density of states at the Fermi level. The interlayer conductance G_{zz} (not resistance) saturates to a low value in each QH state and has peaks at the transitions between the QH states. The peaks in G_{zz} at the transitions are due to the bulk conductivity, but the low value of G_{zz} in the QH states, which is much less than e^2/h, are explained as the conductivity on the side of the sample, i.e., chiral surface state.

Figure 4 shows the temperature dependence of R_{zz} at several magnetic fields. The abrupt decrease below 1 K at zero field is due to the superconducting transition. The arrows indicate the transition from the metallic state to the FISDW state. As temperature decreases, R_{zz} (closed circles) in the QH states for $N\leqslant 3$ quickly increases at the FISDW transition, has a maximum, and then becomes constant at lower temperatures. R_{zz} has almost the same value independent of the quantum number N at low temperatures. On the other hand, at the transitions between the QH states, R_{zz} (open circles) increases and remains at high values.

III. DISCUSSION

In the chiral surface state, the electron motion along the x direction is ballistic, and the back scattering is necessarily precluded as schematically shown in Fig. 1(a).[1,2] The electron motion along the z direction is diffusive and R_{zz} is expected to be independent of temperature. For the TMTSF systems, as the temperature decreases, the electronic system goes into the FISDW state from the metallic state, and the SDW energy gap opens. Since the energy gap increases with decreasing temperature, the steep increase of R_{zz} below the transition temperature (Fig. 4) is explained by the carrier decrease. As temperature further decreases, R_{zz} decreases after having a maximum in the QH states (at least for $N\leqslant 3$). This behavior shows some reduction of the scattering. It is likely that this behavior is ascribed to the formation of the chiral surface state, where the diffusive motion (temperature independent) rather than thermal activation process is dominant. However, we have obtained two unexpected results, (1) N independent R_{zz} in the QH states and (2) sharp peaks in R_{zz} at the transitions between the QH states.

(1) The chiral surface state should give the temperature independent conductivity σ_{zz} along the interlayer (z) direction,[1,3] $\sigma_{zz}=N(e^2/h)K$ and $K=t^2lc/(h^2\nu^2)$, where c is the interlayer distance, l is the mean free pass, and ν is the Fermi velocity in the edge state. The quantum number N corresponds to the number of the conduction channels along the z direction. When the energy gap $E_g(=h\omega_c)$ is much bigger than kT, the scattering from one channel to another is suppressed very much, and σ_{zz} is proportional to N. However, as shown in Figs. 3 and 4, R_{zz} in the QH states, which is proportional to $1/\sigma_{zz}$ for $B\|z$, has the same value independent of N at low temperatures where $kT<h\omega_c$. In addition, the factor K is estimated to be an order of 10^{-1}, by using $c=13.5$ A, $E_F=0.2$ eV, $t=1$ meV, and $l=1\times10^{-6}$ cm. This estimation is somewhat ambiguous, but it is much smaller than the experimental value of K, $\sim10^2$. This fact is very contrast to the GaAs system,[3] where the experimental value $K\sim10^{-3}$ is close to the theoretical estimation. The very large K, i.e., very small R_{zz} for $(TMTSF)_2AsF_6$ may suggest that the interlayer conduction also takes place in the bulk. It means that mobility edge, which is well defined for 2D electron gas, may not be present for the TMTSF systems. The absence of the mobility edge may explain the results that R_{xx} does not completely decrease to zero and that R_{zz} is much smaller than the theoretical estimation in the QH states. However, N independent R_{zz} in the QH states cannot be fully understood by the absence of the mobility edge.

(2) In 2D electron gas, the bulk extended state exists near the center of each Landau level. Therefore, as the field increases, the system passes through an intervening state (bulk metallic state) between the adjacent QH states. The FISDW transitions are very contrast to the case of the 2D electron gas. In the framework of standard theory,[4] the FISDW transition is the first order in nature, which is associated with a discontinuous change of the FISDW nesting vector. No intervening state is necessarily present between the QH states. However, R_{zz} has peaks at transitions between the QH states,

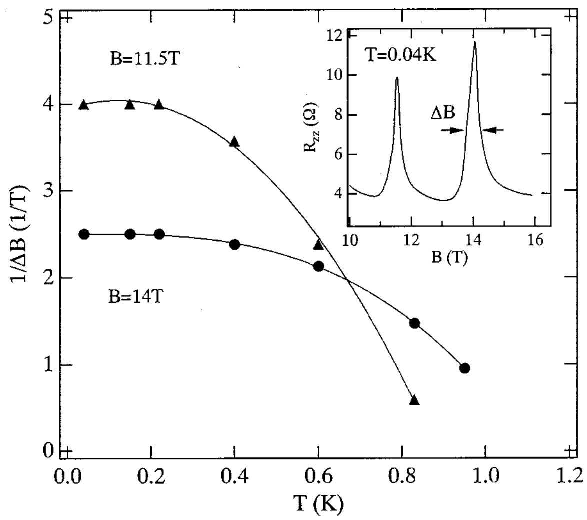

FIG. 5. Inverse of the peak widths of R_{zz},$1/\Delta B$, is plotted as a function of temperature at two different transitions ($B = 11.5$ T and $B = 14$ T). Inset: definition of ΔB.

suggesting the presence of intermediate state between the QH states.

For semiconductors, a scaling phenomenon in the magnetoresistance tensor is found as a function of temperature and magnetic field in the QH regimes.[14] The QH transitions are well characterized by a localization length and the transition width ΔB is expressed by $1/\Delta B \propto T^{-\mu}$, where $\mu \approx 0.42$. This relation shows divergence of $1/\Delta B$ at zero temperature. However, Valfell *et al.* carefully measured the in-plane and Hall resistances for $TMTSF_2PF_6$ at a high pressure and showed that $1/\Delta B$ obtained from the ρ_{xx} curves saturates at low temperatures. In Fig. 5, we present $1/\Delta B$ at two transitions. The value of $1/\Delta B$ increases with decreasing temperature, and saturates below 0.3 K. This behavior is consistent with those obtained by Valfell *et al.*[15] Since the scaling law predicts the divergence of $1/\Delta B$ as temperature decreases, the saturation below 0.3 K strongly suggests the presence of another mechanism. Valfell *et al.* argue that the finite transition width from one QH state to another is a consequence of the broadening of the first-order transition by some disorder of the sample.[15] This disorder is understood in the framework of the Imry and Ma theory.[16] The theory shows that a domain structure (coexistence of two different phases) rather than an uniform structure is energetically favorable near the first-order transition in the presence of a disorder potential coupling to the order parameter. If a domain structure is formed in the crystal, the resistance is expected to increase because of additional scattering of the electrons. Therefore, one possible mechanism of the resistance peaks at the transitions is the formation of some domain structure, which may be the coexistence of two different QH states.

IV. SUMMARY

We have measured R_{zz} in the QH states for the bulk system $(TMTSF)_2AsF_6$. In the QH states, R_{zz} becomes temperature independent at low temperatures, which can be ascribed to the formation of the surface chiral state. The value of R_{zz}, which is much smaller than the theoretical prediction, suggests the presence of the bulk conductivity. However, the observation of N independent R_{zz} remains an open question. The sharp peaks in R_{zz} are found at the transitions between the QH states. The results suggest the existence of intermediate state, which causes the increase of scattering, but the intermediate state is not necessarily expected from standard theory. The overall behavior of R_{zz} is completely different from that observed for GaAs multilayers.

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