Avalanche electron bunching in a Corbino disk in the quantum Hall effect breakdown regime

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We have measured the current noise in a device with Corbino geometry to investigate the dynamics of electrons in the breakdown regime of the integer quantum Hall effect (QHE). In the breakdown regime, the Fano factor of the current noise exceeds 10^3, which indicates the presence of electron bunching. As super-Poissonian current noise is observed only in the breakdown regime, the bunching effect is related to the QHE breakdown. These observations support a QHE breakdown mechanism that involves an electron avalanche.

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I. INTRODUCTION

In quantum Hall effect (QHE) states, the Hall resistance is precisely quantized and the longitudinal resistance vanishes because of the dissipationless current that flows in the edge states [1,2]. The precision of the Hall resistance is utilized as a resistance standard [3], and the edge states are an ideal platform for performing solid-state quantum-optical experiments [4,5].

Under a source-drain bias voltage $V_{\rm sd}$ that is larger than the critical value, however, QHE breakdown occurs: Dissipative QHE states appear, the Hall resistance deviates from the quantized value, and the longitudinal resistance becomes finite [6,7]. QHE breakdown has vexed researchers trying to utilize the QHE states as a resistance standard or for quantum-optical experiments. Although the breakdown mechanism has been studied extensively [8–17], a comprehensive understanding has yet to be reached [18], and thus experimental approaches from different aspects are required.

One promising approach is focusing on the dynamics of the QHE breakdown [19,20]. Studies have shown that the time scale of the QHE breakdown is governed by the thermal stability of the states. However, from a microscopic point of view, the electron dynamics in the current in the QHE breakdown regime have not yet been explored experimentally.

The electron dynamics can be probed through the current noise and quantified by the Fano factor (F) [21]. A Poisson value of $F = 1$ indicates that there is no interaction between the electrons or any correlation in the electron motion, but a larger (smaller) F indicates bunching (antibunching) of electrons in the current. In ballistic conductors, the Pauli exclusion principle restricts F to values that are smaller than unity [22], while for phenomena such as an electron avalanche [23], Kondo correlation [24], and cotunneling [25], F is larger than unity. An electron avalanche, in particular, results in an increased F through carrier multiplication. Bunches of electrons are generated by a triggering electron through impact ionization, and as the electrons in a bunch reach the contacts simultaneously, they are observed as being subject to an attractive interaction.

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Current noise in the QHE breakdown regime has been studied using devices with the Hall bar geometry [26–29], and we previously observed electron-nuclear spin-flip scattering [28] and precursor phenomena of the QHE breakdown [29]. While the QHE breakdown is a dissipative phenomenon that involves bulk states, in Hall bar devices, the majority of the current flow is in the dissipationless edge states. Thus, a geometry that does not produce a current through edge states is needed to investigate the dynamics in the dissipative current. This geometry is offered by a Corbino disk: In the QHE state, the edge current is absent, and the source-drain current $I_{\rm sd}$ is strongly suppressed by the formation of localized bulk states between the contacts. Under a $V_{\rm sd}$ that is larger than the critical value, $I_{\rm sd}$ is finite since the current consists only of electrons that have tunneled or been thermally excited from the contacts into bulk localized states.

QHE breakdown is expected to involve an electron avalanche [11,12], which is a typical phenomenon observed in semiconductors under large electric fields [30], but to date, experimental evidence of carrier multiplication in the QHE breakdown regime is still lacking.

Here, we report on the observation of super-Poissonian excess noise in the QHE breakdown regime of a Corbino device. The power spectrum density (PSD) of the voltage in the Corbino disk was used to estimate the current noise, and F was estimated to be larger than 10^3, indicating electron bunching. Our observations support the hypothesis that an avalanche-type mechanism is involved in the QHE breakdown.

II. EXPERIMENT

The Corbino disk was fabricated on a GaAs/AlGaAs two-dimensional electron gas (2DEG) with an electron density of $n_{\rm e} = 2.3 \times 10^{15}$ m^{-2} and an electron mobility of $\mu = 19$ m^2/V s. The inner contact radius was 100 μm, and the distance between the contacts was $W = 40$ μm [see Fig. 1(a)].

A schematic of the measurement circuit is shown in Fig. 1(b). The Corbino disk was placed in a variable-temperature insert with a base temperature of $T \sim 2$ K, and a resistor $R_{\rm s} = 113$ kΩ was connected in a series to reduce the noise from the measurement components at room temperature. For the noise measurements, a capacitor $C_{\rm p} = 1$ μF and a resistor $R_{\rm p} = 1$ kΩ were connected in parallel with the Corbino disk to reduce the circuit impedance [31]. The

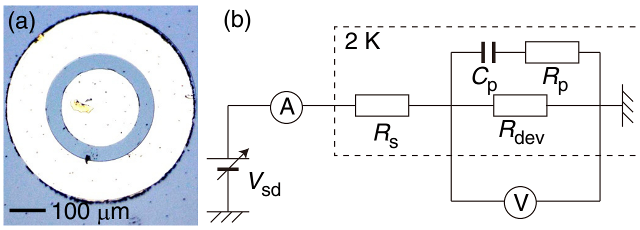

FIG. 1. (Color online) (a) Optical microscope image of the measured Corbino disk. (b) Schematic illustration of the measurement circuit, where $R_s = 113$ kΩ, $C_p = 1$ μF, and $R_p = 1$ kΩ.

magnetic field (B) was applied perpendicularly to the 2DEG, and V_{sd} was applied across the source and drain contacts. A source measure unit (Keithley 6430) was used to measure I_{sd}, and the two-terminal resistance (R_{dev}) and conductivity (σ_{xx}) were determined from $R_{dev} = (1/\sigma_{xx}) = V_{sd}/I_{sd} - R_s$. The net voltage V'_{sd} and average electric field E across the contacts were calculated as $V'_{sd} = \{R_{dev}/(R_{dev} + R_s)\}V_{sd}$ and $E = V'_{sd}/W$, respectively. While the electric field in a Corbino disk has a position dependence, we use E as a representative value here for simplicity. This is based on a previous study [32] in which the critical electric field of the QHE breakdown for a Corbino disk was estimated by E.

The PSD of the voltage noise $S_V(f)$ was obtained over 1–100 kHz using two low-noise amplifiers (NF Corporation LI-75A). The input voltage noise of the amplifiers $S_V^{out} \sim 4 \times 10^{-18}$ V^2/Hz was averaged out using the cross-correlation technique [33,34], and noise signals were collected by an onboard digitizer (National Instruments PCI-5922). Since R_{dev} is effectively much larger than 1 MΩ in the QHE states, the RC cutoff frequency of the circuit $f_c = 1/2\pi RC$, where C is the capacitance of the measurement circuit, is less than 1 kHz without any parallel component. The capacitance of the coaxial cable is about 100 pF/m.

The circuit impedance $R(f) = \{[R_p + 1/(2\pi f C_p)]R_{dev}\}/[R_p + 1/(2\pi f C_p) + R_{dev}]$ is 1 kΩ when $f > 10$ kHz, where f is the frequency of the current, and the current noise $S_I(f)$ was calculated using $S_I(f) = R^2(f)S_V(f)$. Note that the internal capacitance of the Corbino disk is estimated as 100 pF at most, and can be safely neglected.

III. RESULTS AND DISCUSSION

The Shubnikov–de Haas oscillations in the Corbino disk are shown in Fig. 2(a). The oscillation was measured for an increasing B at $T = 2.0$ K and $V_{sd} = 0.1$ V. For $B < 4.0$ T, the Shubnikov–de Haas oscillations are observed as a dip in σ_{xx}, and at around $B = 4.75$ T, the dip in σ_{xx} extends to zero. Under these conditions, the bulk state is insulating because of the formation of the $\nu = 2$ QHE state; it is only when $B = 4.75 \pm 0.1$ T that σ_{xx} is zero at $V_{sd} = 100$ mV, as shown in Fig. 2(b), and we refer to this as the QHE state.

Figure 2(c) shows I_{sd} as a function of V'_{sd} for $B = 4.30$, 4.50, 4.75, and 4.95 T. For $B = 4.30$ T, the 2DEG is in a transition state between Landau levels, and I_{sd} is proportional to V_{sd} as the 2DEG is conductive. At 4.50 T, I_{sd} exhibits a nonlinear relationship with V'_{sd}, since the insulating QHE bulk states start to form. The 2DEG is in the $\nu = 2$ QHE

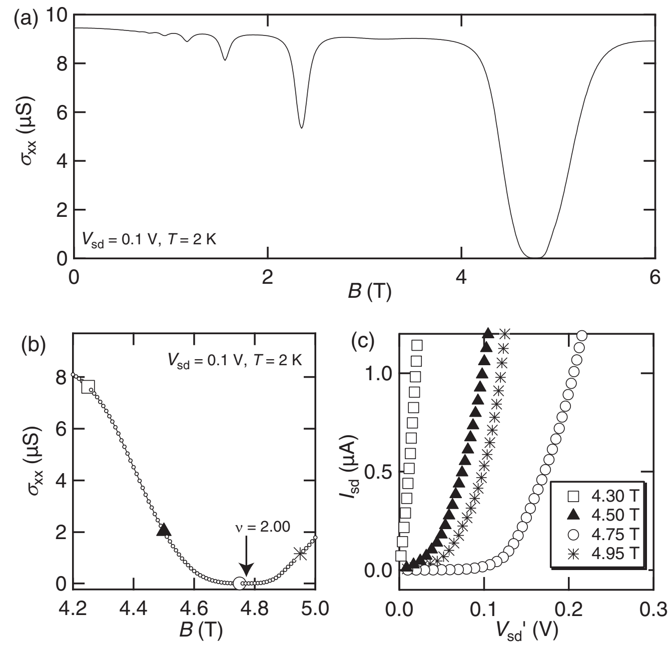

FIG. 2. (a) Shubnikov–de Haas oscillations of the Corbino disk at $V_{sd} = 100$ mV and $T = 2$ K. (b) Details of the Shubnikov–de Hass oscillations around the $\nu = 2$ QHE state indicated by the arrow. (c) Source-drain bias voltage dependence of I_{sd} at $T = 2$ K. Symbols correspond to those in (b).

state at $B = 4.75$ T, and I_{sd} is suppressed until V'_{sd} reaches 100 mV. This suppression is caused by the formation of an insulating QHE bulk state. When $V'_{sd} = 100$ mV, $E = V'_{sd}/W = 25$ V/cm, which is consistent with the breakdown conditions of previous studies [12,32], and the abrupt increase in the current around $V'_{sd} \sim 100$ mV originates from the QHE breakdown. This gives the critical source-drain bias voltage as 100 mV. For $B = 4.95$ T, the current is no longer suppressed because the 2DEG is in a transition state between QHE states.

Figure 3 shows the current-noise PSD over a range of 20–70 kHz for $B = 4.75$ T at $T = 2$ K. The spectrum can be divided into three noise regimes: no excess noise, frequency-dependent excess noise, and frequency-independent excess noise.

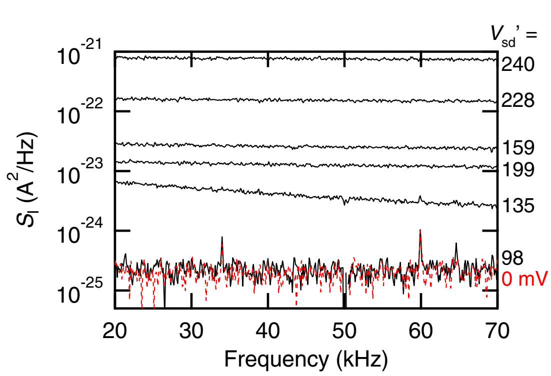

FIG. 3. (Color online) Current-noise PSD obtained for $B = 4.75$ T at $T = 2$ K and several V'_{sd}'s. The dotted line is obtained at $V'_{sd} = 0$ mV.

In the no-excess-noise regime, the thermal noise from R_p dominates the noise spectrum, the current noise is independent of V'_{sd} for $V'_{sd} < 100$ mV, and the current noise exhibits a white noise spectrum. Between 20 and 70 kHz, S_I is $(1.87 \pm 0.57) \times 10^{-25}$ A^2/Hz, which corresponds to the noise temperature $T_{noise} = 3.4 \pm 1.0$ K of the 1 kΩ resistor. As the external noise is eliminated by the cross-correlation technique, the noise in this regime originates from the Corbino disk and R_p, and so T_{noise} corresponds to the actual electron temperature in the Corbino disk and R_p.

In the frequency-dependent excess-noise regime, I_{sd} increases as V'_{sd} increases from 100 to 150 mV, and the excess noise has a frequency dependence of $S_I = (1/f)^\alpha + \beta$ with $\alpha \sim 0.7$. The frequency dependence most likely arises from resistance switching due to fluctuations between the bistable states [20,35]. This noise is observed only when I_{sd} is smaller than a few hundred nanoamperes, and the conditions for frequency-dependent noise are consistent with the conditions for bistable states noted in previous studies.

In the frequency-independent excess-noise regime, I_{sd} shows an almost linear dependence on V'_{sd}, and for $V'_{sd} >$ 150 mV, S_I is a few orders of magnitude larger than S_I for $V'_{sd} < 100$ mV. The noise S_I is around 10^{-21} A^2/Hz at $V'_{sd} =$ 240 mV. The amplitude of the current noise should correspond to $T_{noise} = 10^4$ K, but the value is too large to be explained by electron heating caused by QHE breakdown [13,29].

Focusing on the frequency-independent excess-noise regime, the excess noise S is shown as a function of I_{sd} in Fig. 4(a) for $B = 4.30$, 4.50, 4.75, and 4.95 T. The excess noise calculated according to $S = 2eI_{sd}F$ for $F = 1$, 10, 10^2, and 10^3, where e is the charge quanta, is also shown. As B increases from 4.30 to 4.50 T, S is proportional to I_{sd} and the corresponding F value increases from ~0.5 to >1. For the $\nu = 2$ QHE state ($B = 4.75$ T), S varies as a function of I_{sd} and is orders of magnitude larger than the value at 4.30 T. In the transition between the QHE states ($B = 4.95$ T), S is almost proportional to I_{sd} and smaller than the value at 4.75 T. Variations in S possibly originate from disorder in the potential landscape of the Corbino disk, which would strongly affect the charge dynamics in the breakdown regime.

To clarify the relationship between the super-Poissonian noise and the QHE breakdown, we examined the average F value $\bar{F}$ and σ_{xx} as a function of B [Fig. 4(b)]. We found that $\bar{F}$ was a maximum at 4.85 T, which corresponds to the 2DEG being in the QHE state, and it is only around the QHE state that $\bar{F}$ becomes super-Poissonian. Therefore, we can conclude that the super-Poissonian excess noise is a direct consequence of the QHE breakdown.

As $F > 0$ is obtained with the Corbino disk, the disk is different from usual bulk resistors, which gives us $F = 0$ because of electron scattering events that average out the shot noise [21,36]. In samples in the variable-range-hopping (VRH) regime, F is finite and decays with the sample length, which agrees with theoretical models [37–39]. The Corbino disk in a transition between QHE states would be in the VRH regime, but while VRH-regime models explain the sub-Poissonian noise in this regime, they do not explain the super-Poissonian noise observed around the $\nu = 2$ QHE state.

One recent study has explained the Poissonian shot noise in a 2DEG in the VRH regime by using a vacuum tube analogy [40]; the most resistive hop dominates the excess noise, and the excess noise is unity because the electron conduction at the most resistive site is independent of each other, similar to the case of hot electron emission from a cathode.

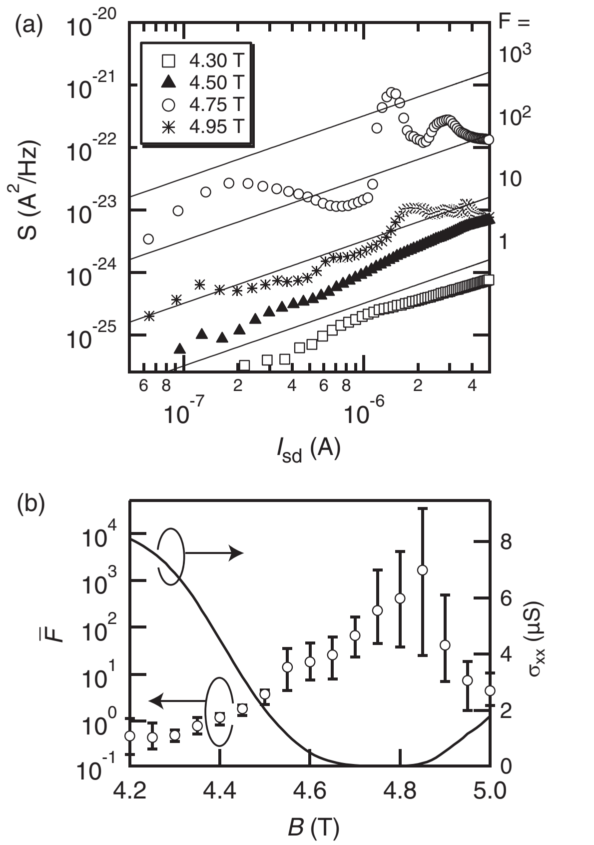

FIG. 4. (a) Excess noise S as a function of I_{sd}. Solid lines are given by $S = 2eI_{sd}F$ for $F = 10^0, 10^1, 10^2$, and 10^3. (b) Applied magnetic field B dependence of $\bar{F}$ and σ_{xx}. Plots are $\bar{F}$ over $I_{sd} = 0.1$–5 μA, and the error bars correspond to the maximum and minimum values of F in the range $I_{sd} = 0.05$–5 μA.

We can extend this vacuum tube analogy to involve electron avalanche and explain the super-Poissonian excess noise in the Corbino disk. The analogy differs in terms of the "vacuum" that the electrons pass through; i.e., in the Corbino disk case, electrons enter a semiconductor filled with localized electrons, and interactions with these localized electrons result in impact ionization, carrier multiplication, and, finally, QHE breakdown. When the bunched electrons reach the drain contact almost simultaneously, S is enhanced, and an electron bunch of N electrons is observed as a particle of charge Ne. The resultant F value therefore carries information about the typical value of N, which is related to the multiplication factor of the avalanche. We thus conclude from our observations that the super-Poissonian noise originates from the carrier multiplication of the electron avalanche. In other words, the super-Poissonian noise is direct evidence of carrier multiplication in the QHE breakdown regime.

IV. CONCLUSION

We have observed super-Poissonian excess noise in a Corbino disk in the QHE breakdown regime. The excess noise was estimated as F to exceed 10^3. We have shown that a vacuum tube analogy that involves an electron avalanche explains the super-Poissonian excess noise. At the transition of the QHE states, the excess noise is sub-Poissonian, and super-Poissonian excess noise is only observed in nonequilibrium QHE states, and thus we conclude the super-Poissonian excess noise is related to the QHE breakdown and indicates the presence of electron bunching in the current, which is consistent with the avalanche picture of QHE breakdown.

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