Shot Noise Induced by Electron-nuclear Spin-flip Scattering in a Nonequilibrium Quantum Wire

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We study the shot noise (nonequilibrium current fluctuation) associated with dynamic nuclear polarization in a nonequilibrium quantum wire (QW) fabricated in a two-dimensional electron gas. We observe that the spin-polarized conductance quantization of the QW in the integer quantum Hall regime collapses when the QW is voltage biased to be driven to nonequilibrium. By measuring the shot noise, we prove that the spin polarization of electrons in the QW is reduced to ~0.7 instead of unity as a result of electron-nuclear spin-flip scattering. The result is supported by Knight shift measurements of the QW using resistively detected NMR.

Nuclear spins in solids are well isolated from their environment, and their coherence times can be much longer than that of electron spins. This fact makes them a promising candidate as qubits and memories in solid-state devices. Dynamic nuclear polarization (DNP) is the hyperfine-mediated transfer of spin polarization from electrons to nuclei, and can be used to initialize the nuclear spins before a computation. Quantum wires (QWs) defined in a two-dimensional electron gas (2DEG) in the quantum Hall (QH) regime could be used for quantum information processing since coherent control of the nuclear spin state has been demonstrated. DNP in these systems is triggered by voltage biasing the edge state but the detailed mechanism of DNP in a small confined region such as a QW is not fully understood.

Because DNP is expected to be compensated by the spin degree of freedom of electrons, the resultant electron depolarization further provides essential information on the nature of the electron-nuclear interaction. The Knight shift measurement has been applied to address DNP by resistively detected NMR (RDNMR), although, to the best of our knowledge, the direct observation of the electron-nuclear spin-flip process remains to be demonstrated. Shot noise (nonequilibrium current fluctuation) could enable us to further address DNP because it is generated by the partition process of electrons at scatterers. Actually, shot noise enabled us to quantitatively discuss electron-spin-dependent transmission probabilities, which is impossible through conventional conductance measurements alone. To the best of our knowledge, however, DNP has not been investigated by using shot noise.

The purpose of this Rapid Communication is to demonstrate that shot noise can serve to investigate the electron-nuclear interaction in nonequilibrium nanostructures. We prove that the shot noise is induced by the electron-nuclear spin-flip scattering process in a nonequilibrium QW in the integer QH regime. By combining the conductance and noise measurements, we deduce finite electron spin depolarization as a result of DNP, which is confirmed to be consistent with the result of the Knight shift measurement via RDNMR.

Figure 1(a) shows a schematic measurement setup with the scanning electron microscopy (SEM) image of a QW fabricated on a AlGaAs/GaAs heterostructure 2DEG [with an electron density of $2.3 \times 10^{11}$ cm$^{-2}$ and mobility of $1.1 \times 10^{6}$ cm$^2$/Vs]. The 1-$\mu$m-long QW is defined by two metallic gate electrodes by applying gate voltages $V_g$ and $V_{cg}$. We used a resonant circuit with a homemade cryogenic amplifier for the noise measurement and a one-turn coil around the device for RDNMR. The source-drain bias voltage $V_{sd}$ is applied to the QW to simultaneously measure the dc current, the differential conductance, and the noise in the two-terminal geometry. The noise spectral density centered around 2.5 MHz is obtained as reported before. By applying

**FIG. 1.** (a) Schematic diagram of the measurement setup with a SEM image of a QW fabricated on GaAs/AlGaAs 2DEG. (b) Equilibrium QW conductance as a function of $V_g$. At the conductance plateau at $e^2/h$, which we focus on in this paper, only the outer edge channel transmits electrons whereas the inner one is reflected. The two channels are spin polarized, as schematically shown in (a) by $\uparrow$ and $\downarrow$.**
a magnetic field ($B$) perpendicularly to the 2DEG, we tune the bulk 2DEG at the QH state with a filling factor $\nu \approx 2$. The base electron temperature ($T$) in the QW, estimated by the thermal noise measurement, was 80 mK. In this condition, the Zeeman electron energy $\Delta g = |g^* \mu_B B| \sim 120 \mu eV$ at 5 T is much larger than the thermal energy ($k_B T \sim 7 \mu eV$ at 80 mK), where $g^*$ is the $g$ factor of bulk GaAs, $\mu_B$ is the Bohr magneton, and $k_B$ is the Boltzmann constant.

Figure 1(b) shows the equilibrium conductance of the QW as a function of $V_g$. The conductance plateau at $2e^2/h$ for $V_g \gtrsim -0.9 \, V$ reflects the $\nu = 2$ QH state in the bulk 2DEG. Because the edge states are fully spin polarized, the QW conductance shows another plateau at $e^2/h$ between $V_g = -1.25$ and $-1.75 \, V$, where only the outer edge channel passes through the QW with the inner one perfectly reflected, as schematically presented in Fig. 1(a). Below we focus on this single-edge regime.

Figure 2(a) shows the differential conductance $G$ at 4.5 T as a function of $V_{sd}$ obtained for $V_g = -1.6, -1.5, -1.4,$ and $-1.3 \, V$. The behavior of $G$ can be divided into three regions depending on the value of $|V_{sd}|$, namely, the "(quasi-)equilibrium," the "transient," and the "steady" regimes. In the small-$|V_{sd}|$ region [(quasi-)equilibrium], $G$ remains constant at $e^2/h$. When $|V_{sd}|^2$ is increased beyond a certain threshold voltage, typically 50–100 $\mu V$ depending on $V_g$, $G$ starts to deviate from the quantized value and shows a clear dip structure (transient regime). In this regime, $G$ shows hysteresis behavior depending on the sweep direction of $V_{sd}$ and exhibits temporal variation over minutes, as we discuss later in Fig. 3. [Note that the curves in Fig. 2(a) were obtained by sweeping $V_{sd}$ in the backward direction.] The threshold value of $|V_{sd}|$ for entering this transient regime falls at the same order as $\Delta Z$ and almost linearly increases with $B$. Therefore, the observed collapse of the conductance quantization is related to the electron scattering between Zeeman-split Landau levels. Consistent with this fact is that when the filling factor is set to one for both the bulk and the QW, the collapse of the conductance quantization is observed to occur at much larger $|V_{sd}|$. The upper bound of $|V_{sd}|$ for the transient regime is determined by the broadening width of Landau levels. By further increasing $|V_{sd}|$ (typically $\sim 200 \mu V$), the QW enters the steady regime, where the temporal variation and the hysteresis in $G$ disappear.

Now we discuss the excess noise $S$ as a function of $V_{sd}$, which were measured simultaneously with $G$ as shown in Fig. 2(b). $S$ is obtained by subtracting the thermal noise from the total current noise spectral density. Around $V_{sd} = 0 \, V$, the QW shows no excess noise because of the dissipation-less QH edge transport. In contrast, finite excess noise is generated in the nonequilibrium regimes. In the transient regime, $S$ as well as $G$ show temporal variation. Remarkably, when the QW enters into the steady nonequilibrium regime at $|V_{sd}| \gtrsim 200 \mu V$, the excess noise linearly increases as $|V_{sd}|$ increases.

The shot noise is characterized by the Fano factor defined by $F \equiv S/2eI$, where $e$ is the electron charge and $I$ is the current. In Fig. 2(c), the Fano factors derived from the measured noise $S$ and the measured current $I$ are shown for $V_g$'s corresponding to the data shown in Figs. 2(a) and 2(b). In the steady regime, the differential conductance is almost constant, whereas $S$ linearly increases as $|V_{sd}|$ increases. The obtained Fano factor is, therefore, almost constant, as shown by horizontal dashed lines in Fig. 2(c), which is a characteristic signature expected in conventional shot noise theory. In addition, $F$ systematically depends on $V_g$; as $V_g$ changes from $-1.6$ to $-1.3 \, V$, namely, as the width of the QW increases, $F$ monotonically increases from 0.19 to 0.26.

The above experimental result enables us to decompose the spin-dependent transmission probabilities of the edge channels as follows. In the $\nu = 2$ QH states, there are only two relevant edge channels, namely, spin-up and spin-down channels, with transmission probabilities of $\tau_u$ and $\tau_d$, respectively [see Fig. 1(a)]. On the assumption that the transmission is independent of electron energy, the conductance $G$ and the Fano factor $F$ are given as $G = G_0(\tau_u + \tau_d)$ and $F = [\tau_u(1-\tau_u) + \tau_d(1-\tau_d)]/(\tau_u + \tau_d)$, respectively (where $G_0 \equiv e^2/h$). Based on this model, we deduce $\tau_u$ and $\tau_d$ with the constraint that $0 \leq \tau_u, \tau_d \leq 1$, and the Fano-factor-based electron spin polarization $P_F$ defined
by \( P_F = |\tau_2 - \tau_1|/|\tau_1 + \tau_1| = \sqrt{2G_0(1-F)/G-1} \) is obtained. Naturally, in the (quasi-)equilibrium regime, where no excess noise is present even when \( |eV| > k_BT \), \( F = 0 \) and thus \( P_F = 1 \). This is, however, not the case for the steady regime. For example, at \( V_g = -1.3 \text{ V} \), we obtained \( P_F \approx 0.62 \) as \( G = 1.06G_0 \) and \( F = 0.26 \), as shown in Figs. 2(a) and 2(c), respectively.

Figure 2(d) shows \( P_F \) as a function of \( V_g \). Remarkably, \( P_F \) monotonically decreases as the width of the QW increases. We confirmed that a similar result was also obtained for another QW with \( 2 - \mu \text{m} \) length. Such a systematic dependence of \( P_F \) on \( V_g \) tells us that the electron scattering that causes the shot noise mainly takes place inside the QW. Furthermore, because the total spin momentum should be conserved, the reduction of \( P_F \) from unity, namely, finite electron depolarization, suggests the transfer of spin momentum to other degrees of freedom, at least partially, to the nuclear spin.

Henceforth, we discuss the result of RDNMR to confirm these findings derived from the shot noise measurement. We focus on the transient regime, where QW shows a hysteresis behavior depending on the \( V_{sd} \) sweep direction, as shown in Fig. 3(a)(b). In accord with this fact, when \( V_{sd} \) is suddenly increased from 0 to 180 \( \mu \text{V} \), the conductance gradually increases from 0.66\( e^2/h \) to 0.96\( e^2/h \) with a typical time scale of minutes [solid circles in Fig. 3(b)]. Such behavior was attributed to the effective hyperfine field of DNP as reported recently. Indeed, the observed temporal variation of \( G \) can be almost eliminated by radio frequency (rf) irradiation with the NMR frequency of \( ^{75}\text{As} \) (36.408 MHz at \( B = 5.0 \text{ T} \) ) [open circles in Fig. 3(b)]. The NMR signal was also detected for \(^{69}\text{Ga} \). The result provides strong evidence that DNP occurs in the nonequilibrium regime.

The Knight shift measurement based on RDNMR is performed to obtain the Knight-shift-based electron spin polarization \( P_K \), which enables us to show that the above \( P_F \) reflects the spin polarization in the QW. The measurement consists of three steps: “creation,” “irradiation,” and “detection.” First, we set the QW in the transient nonequilibrium regime to prove that the DNP is created in the QW (creation) via the temporal variation of \( G \). After waiting a certain time (typically 3 min) for the DNP development to almost saturate, the QW is set at a given condition and is irradiated by the rf waves for a few seconds (irradiation). Finally, the QW is returned to the initial transient state and the temporal variation of \( G \) is again monitored (detection). By setting the QW at an arbitrary state in the irradiation step, the NMR spectrum for that state is obtained. If DNP created in the Creation step is destroyed by the on-resonance rf waves, we detect the finite temporal variation of \( G \) by the redevelopment of DNP in the QW.

The image plot in Fig. 4(a) shows a typical result of the conductance in the Detection step obtained at \( V_g = -1.6 \text{ V} \) and \( B = 5.0 \text{ T} \) as functions of the RF frequency and the elapsed time after rf irradiation. The QW was set at \( V_{sd} = 280 \mu \text{V} \) in the irradiation step. Reference NMR spectra corresponding to \( P_K = 0 \) and \( P_K = 1 \) are shown at the top and the bottom, respectively. All the data shown in (b) were taken at \( V_g = -1.60 \text{ V} \). (c) \( P_K \) obtained by the RDNMR (upper panel) and the equilibrium conductance (lower panel) as a function of \( V_g \). The dotted curve in the upper panel is a guide to the eye.
duction electrons that couple the nuclear spins under rf irradiation. For $P_K = 1$, the spectrum is obtained by setting $V_{sd} = 0$ in the irradiation step. Because only the fully spin-polarized electrons are present in the equilibrium QW [see Fig. 1(a)], the NMR frequency gives a reference for the electron distribution of 100%, which is determined to be 36.403 MHz, as shown in Fig. 4(b). The signal unexpectedly shows a dip instead of a peak, which might be relevant to subtle spin dynamics in the $\nu = 1$ state. Based on the results shown in Fig. 4(b), if we assume that the Knight shift is proportional to the electron spin polarization, we find that for the electrons in the QW $P_K = 6$ kHz/16 kHz $\sim 0.4$ for the transient regime and $P_K = 8$ kHz/16 kHz $\sim 0.5$ for the steady regime.

The upper panel of Fig. 4(c) shows the polarization $P_F$ obtained in the steady regime for several $V_g$'s. In the lower panel, the corresponding equilibrium conductance is shown. $P_K$ decreases as the width of the QW increases (as $|V_g|$ decreases). This behavior is consistent with that of $P_F$ obtained via the shot noise shown in Fig. 2(d). Quantitatively, $P_F$ and $P_K$ are different from each other. This is probably because we simply assume that the Knight shift is proportional to the electron spin polarization and neglect that it also depends on the electron density. Nevertheless, the behavior consistently observed in the two totally different methods supports the notion that shot noise can serve as a useful tool for detecting electron polarization as RDNMR does.

The width of the NMR spectra also provides us with useful information on DNP. As shown in Fig. 4(b), the full width at half maximum (FWHM) for the spectrum of the depleted QW is $\sim 2$ kHz, whereas those of the other spectra are about 8 kHz. The width that is broader than that of the bulk GaAs is attributed to the distribution of the electron density in the 2DEG confined in the heterostructure. Because no electrons are present in the depleted QW, no electron distribution exists and the width becomes smaller than those obtained with electrons present inside the QW. This observation, as well as the $V_g$-dependent shot noise, supports the fact that the observed DNP comes only from the electronic states inside the QW.

Finally, we propose the mechanism of DNP to explain all the experimental observations as follows. In the nonequilibrium QW in the QH regime, DNP is induced by electron scattering between the spin-resolved Landau levels inside the QW. In this process, the electron spin flips and nuclear spin flips through the hyperfine interaction. The excited electrons tunnel in the localized second Landau levels to escape the QW, providing a partition process of the conduction electrons at the QW to generate the shot noise. The unoccupied second Landau levels are only present inside the QW. Therefore, as the QW becomes wider, the number of unoccupied Landau levels available for electron scattering increases, leading to the large depolarization shown in Figs. 2(d) and 4(c).

In conclusion, we observed shot noise induced by the electron-nuclear interaction and the resultant electron depolarization in a nonequilibrium QW. Although so far the RDNMR method has been mainly used to electrically investigate the DNP in a semiconductor, the present work proves that shot noise is also useful since it directly probes electron-nuclear spin-flip scattering. Further investigations in this direction will open a different way to electrically manipulate the coherence of local nuclear spins in semiconductor nanostructures.

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The RDNMR was performed for the same QW, the results of which are shown in Figs. 1 and 2, but in a different cooldown. Because of this, the $V_g$ dependence of $G$ is not the same between Fig. 1(b) and Fig. 4(c). We have checked that the noise measurement gives a consistent result in this cooldown for RDNMR.

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