Resistance fluctuations in GaAs/Al_xGa_{1-x}As quantum point contact and Hall bar structures

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We study low-frequency noise in selectively doped GaAs/Al_xGa_{1-x}As quantum point contact and Hall bar structures. Experiments are carried out at 4.2 K and constant magnetic fields where noise in both diagonal and Hall voltages is measured using a four-terminal lock-in technique. In all cases, for low currents and low frequencies, we find the size of excess voltage noise power to be quadratic in current and, furthermore, Hall voltage noise power to be quadratic in magnetic field. Resistance fluctuations of the quantum point contact samples are mostly dominated by a single two-level or multilevel switching event that leads to a Lorentzian noise spectrum, whereas resistance fluctuations of the Hall bar structures exhibit $1/f$ noise, which results from the superposition of many independent switching events. Three possible sources of $1/f$ noise, i.e., fluctuations in carrier density, mobility, and quantum interference corrections, are considered in the analysis of the Hall bar data. From the size of $1/f$ noise in the Hall voltage, we deduce an upper bound for the size of carrier density fluctuations that is so small that we rule out electron trapping as a main source of resistance fluctuations in the quantum point contact structures. Instead, we explain observed low-frequency noise in both mesoscopic and macroscopic structures by fluctuations in the remote impurity configuration. [S0163-1829(97)05239-9]

I. INTRODUCTION

Studying the noise of semiconductor devices is important to understand the performance of electronic circuits as well as physical processes that govern the transport of carriers. Many processes contribute to the noise of a practical device. Based on their physical origin, we can classify different kinds of noise into two categories. The first kind of noise is directly caused by the electronic processes and reflects the granularity of the carriers and the stochastic nature of the transport mechanism. Thermal noise and shot noise belong to this category. A second kind of noise arises from the coupling of the electronic processes to the fluctuations of its surroundings. This is an indirect noise because it reflects various processes occurring around the conductor. Changes in the impurity configuration of a conductor and various trapping detrapping effects are examples of this type of noise. This second type of noise always manifests itself as fluctuations in sample resistance and we will use the term resistance fluctuations to describe this type of noise.

Resistance fluctuations can only be understood by identifying the physical processes that lead to changes in resistance. Despite earlier attempts to give a universal explanation to resistance fluctuations, it is now well accepted that such fluctuations are very much dependent on the particular system under investigation.[1] For example, resistance fluctuations in Si metal-oxide-semiconductor field-effect transistors, amorphous conductors, and superconducting films have different physical origins.

In this paper we are interested only in resistance fluctuations of a two-dimensional electron gas (2DEG) in selectively doped GaAs/Al_xGa_{1-x}As heterostructures. This system, because of its superior transport properties, has been widely used in device applications as well as in low-dimensional electron physics studies. The contributions of different scattering mechanisms to the resistance of the system has been studied in detail[2] and many aspects of its electron transport are now well understood. However, we do not yet have an in-depth understanding of its resistance fluctuations, which have been found to be important in mesoscopic structures fabricated from such heterostructures.[3–9] Various mechanisms, such as trapping of electrons,[4–6] changes in the remote impurity configuration,[7] and DX centers,[8] have been proposed as the source of such fluctuations.

In order to identify the physical origin of these fluctuations, we made noise measurements on both macroscopic and mesoscopic structures. The frequency spectra of resistance fluctuations are quite different in these two structures; in the former case, the resistance fluctuations are a superposition of many independent physical processes, whereas in the latter case a single physical event (sometimes a few) can dominate the resistance fluctuations. The fluctuations in macroscopic samples can be thought of as a superposition of the many switching events observed in mesoscopic structures. Therefore, measurements on these two sets of samples are intimately related and complement each other. For example, switching events observed in mesoscopic samples can give information about emission and capture rates of a single defect, whereas $1/f$ noise observed in macroscopic samples can tell us about the spatial density of such defects.

We also carried out experiments with Hall bar structures under a magnetic field in which fluctuations in both diagonal and Hall resistances were measured. The primary motivation for measuring resistance fluctuations in the Hall voltage is to quantify carrier density fluctuations in the 2DEG, which cannot be done by diagonal resistance measurements alone since the fluctuations in diagonal resistance depend on both carrier density and mobility fluctuations. From the fluctuations in

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Hall resistance, we obtain an upper bound for the carrier density fluctuations that is so small that we can rule out electron trapping as a main source of the switching noise in quantum point contact (QPC) structures. We also rule out the possible contribution of DX centers based on multilevel switching noise in some of our QPC's as well as the observed energy difference between different states of the QPC's. However, fluctuations in the remote impurity configuration (Si donors in $Al_xGa_{1-x}As$) can explain our noise data from both the mesoscopic and macroscopic structures.

II. THEORETICAL BACKGROUND

A. Switching noise

The simplest case of resistance fluctuation is a two-level switching noise, also known as random telegraph noise, where the resistance of the sample switches instantaneously between two resistance values of R_1 and R_2. The sample will be referred to as being in state 1 or state 2 depending on the current resistance value of the sample. Switching is a random process characterized by two lifetimes τ_1 and τ_2, where $1/\tau_1$ and $1/\tau_2$ are the probabilities per unit time for transitions from state 1 to state 2 and state 2 to state 1, respectively. The power spectrum of two-level switching noise has been shown to be Lorentzian:[10]

$$S_R(f)=\frac{(\Delta R)^2}{\tau_1+t_2}\left(\frac{1}{(1/\tau)^2+(2\pi f)^2}\right), \qquad (1)$$

where $\Delta R=R_1-R_2$ and $1/\tau=1/\tau_1+1/\tau_2$.

In general, the resistance of a sample can take more than two resistance values. If n states are involved, the switching process would be characterized by $n(n-1)$ time scales τ_{ij}, where $1/\tau_{ij}$ is the probability per unit time for a transition from state i to state j. All of these transitions are expected to obey a Poisson distribution.

Without knowing the physical origin of the switching noise, one can gain considerable insight by mapping the switching process to an energy versus configuration space diagram. In many cases, such a picture is successfully applied to characterize defects that cause switching noise.[11] For example, in the two-level case, the difference in energies of the two states can be obtained from the ratio of lifetimes $E_2-E_1=k_BT\ \ln(\tau_1/\tau_2)$, where E_2-E_1 is the energy difference between state 2 and state 1, k_B is the Boltzmann constant, and T is the temperature. Furthermore, in some cases, the activation energy for going from one state to another can be obtained from the temperature dependence of the lifetimes. This kind of information about energy levels and activation energies can be crucial in the identification of the physical origin of such switching processes.

B. 1/*f* noise

A rich variety of macroscopic conductors exhibit low-frequency resistance fluctuations with a power spectrum close to $1/f$. Unlike switching noise, the resistance of such conductors is not limited to a finite number of resistance values. Such fluctuations are now understood in terms of a superposition of many independent switching events occurring in the macroscopic conductor. If we limit ourselves only to two-level switching events, we can express the noise spectrum of a macroscopic sample as

$$S_R(f)=\sum_{k=1}^{N}\frac{(\Delta R)_k^2}{\tau_{1k}+\tau_{2k}}\left(\frac{1}{(1/\tau_k)^2+(2\pi f)^2}\right), \qquad (2)$$

where N is the total number of switching events, τ_{1k} and τ_{2k} are the two lifetimes of the kth switching event, and $1/\tau_k=1/\tau_{1k}+1/\tau_{2k}$.

It can be shown that in the limit of large N, if one assumes a uniform distribution of lifetimes, $S_R(f)\propto 1/f$. However, this assumption is not always justified. In fact, depending on the distribution of lifetimes, $S_R(f)$ can deviate from $1/f$. Thus the noise spectrum is more generally written as $S_R(f)\propto 1/f^{\alpha}$, where α is a noise exponent close to 1.

The size of $1/f$ noise depends on the total number of switching sites as well as the typical resistance fluctuation contribution of a switching site $\langle(\Delta R)_k\rangle$. For a homogeneous macroscopic sample, the total number of switching sites is proportional and the typical $\langle(\Delta R)_k\rangle$ is inversely proportional to the area of the sample. This implies that $S_R(f)$ scales inversely with the area of the sample. This is a very general result,[12] also known as Hooge's law, which enables us to deduce bulk properties, such as the density of switching sites, from the measured $1/f$ noise. It is important to note that the contact-related $1/f$ noise that is present in many real systems does not scale with the area of the sample. Thus it is critical to check the area dependence of $1/f$ noise to make sure that the measured $1/f$ noise is not due to contact resistance fluctuations.

In general, resistance fluctuations are attributed to changes in either carrier density or carrier mobility of the sample. However, at very low temperatures, there are contributions to the resistance of the sample due to quantum interference effects. Such corrections are very sensitive to the impurity configuration of the sample; thus fluctuations in the impurity configuration can also lead to $1/f$ noise.[13] Unlike $1/f$ noise due to carrier density or mobility fluctuations, the contribution of quantum interference $1/f$ noise has an upper bound that is on the order of universal conductance fluctuations. So far quantum interference $1/f$ noise has only been observed in Bi wires[14] and in most cases it is overwhelmed by either carrier density or mobility fluctuations.

III. SAMPLE FABRICATION

We studied samples of high-quality selectively doped $GaAs/Al_xGa_{1-x}As$ heterojunctions grown by molecular-beam epitaxy (from two different machines). We observe that samples from similar high-quality 2DEG heterostructures behave similarly. Here we will present results obtained from only one heterostructure. This heterostructure is grown on an undoped GaAs substrate and consists of a 1.5-μm-thick undoped GaAs buffer layer, a 43-nm-thick $GaAs/Al_{0.35}Ga_{0.65}As$ spacer layer, a 35-nm-thick Si-doped $GaAs/Al_{0.35}Ga_{0.65}As$ layer with a dopant density of $5\times10^{18}\ \mathrm{cm}^{-3}$, and a 20-nm-thick GaAs cap layer.

Hall bar structures are fabricated by standard lithography followed by wet etching. Indium contacts are alloyed at 400 °C for 2 min to form Ohmic contacts to the 2DEG. Magnetoresistance measurements on these Hall bar structures are

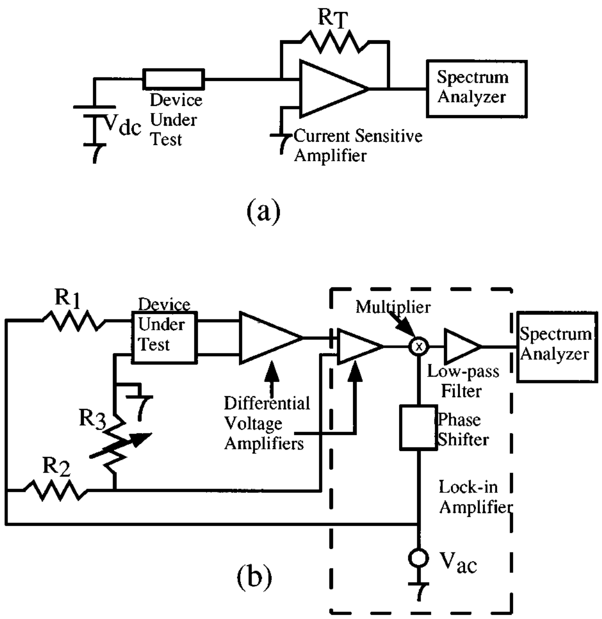

FIG. 1. Block diagrams of (a) two-terminal dc and (b) four terminal ac noise measurement setups used in our experiment.

carried out at 4.2 K to characterize the 2DEG; from these measurements we deduce electron density and mobility values of $n = 1.6\times10^{11}$ cm^{-2} and $\mu = 5\times10^5$ cm^{-2}/V s, respectively.

For the QPC structures, indium contacts are first alloyed to form Ohmic contacts to the 2DEG and then metal gates that are separated from each other by 0.4–0.5 μm are patterned on the surface by electron beam lithography. At applied gate voltages of less than -0.3 V the electrons under the gates are depleted to form the QPC. The electrical width of the contact is controlled by varying the gate voltages. Typically, our QPC's exhibit conductance steps in units of $2e^2/h$ as a function of gate voltage at $T = 1.5$ K.

IV. MEASUREMENT TECHNIQUES

Different noise measurement techniques are used depending on the sample resistance and the size of the resistance fluctuations. We will discuss the operation principles and the limitations of the two noise measurement setups used in our experiment. The circuit diagrams showing only the essential components of these setups are given in Fig. 1; cable capacitances, biasing circuits and filters, and ground isolation buffer amplifiers are not shown in these circuit diagrams.

The measurement setup shown in Fig. 1(a) is most suited for measuring high-resistance samples (100 kΩ or higher). This setup is for a two-terminal measurement where a dc voltage bias is applied to the device under test and the device current is measured by a low-noise current-sensitive amplifier, which is fed to a spectrum analyzer. Quantum point contact samples are measured using this setup.

For lower-resistance samples, we current bias these devices and measure the voltage noise. If a dc bias is used, $1/f$ noise of the preamplifier would limit the performance of the setup at low frequencies.[15] We find our low currents that the $1/f$ noise of the preamplifier overwhelms the voltage fluctuations in our Hall bar samples.

The ac noise setup shown in Fig. 1(b) is used to overcome this problem of preamplifier $1/f$ noise. Similar ac techniques are used by various groups to measure resistance fluctuations.[16] We used an ac excitation of 1.1 kHz, which is greater than the corner frequency of our preamplifier (150 Hz). The measurement bandwidth is limited by the time constant of the lock-in amplifier. Typically, we used a time constant of 10 ms and limited our measurements to a bandwidth of 10 Hz. To eliminate $1/f$-type fluctuations in the lock-in amplifier (such as fluctuations in the amplitude of the ac excitation) a bridge configuration is used. The bridge circuit is formed by three resistors R_1, R_2, and R_3 and the four-terminal sample and the preamplifier. R_3 is a variable resistor used for nulling the bridge circuit. R_1 is chosen to be much bigger than the sample resistance in order to suppress the contribution of contact $1/f$ noise. Furthermore, to make sure that there was no significant contribution from contact $1/f$ noise, we carried out all our measurements using two different R_1 values (10 MΩ and 500 kΩ) and found that the measured resistance fluctuations were independent of R_1. The setup is also tested by measuring metal film resistors; no $1/f$ noise was observed in the frequency range 0.05–10 Hz. All the noise data from Hall bar samples are obtained using this ac setup.

V. EXPERIMENTAL RESULTS

A. Quantum point contact samples

We made noise measurements on QPC samples at 4.2 K and zero magnetic field using the dc noise measurement setup of Fig. 1(a). We limited our measurements to the single-channel limit of the QPC (resistance higher than $h/2e^2$) where low-frequency noise is most pronounced.

Figure 2(a) shows a typical noise spectrum of a QPC sample. The spectrum has Lorentzian shape with a corner frequency of 20 Hz. The amplitude of the noise scales quadratically with current, indicating that it is due to resistance fluctuations. For this sample, we also measured real time traces of QPC conductance; a typical trace is shown in Fig. 2(b). This QPC sample exhibits three distinct conductance states. Since more than two states are involved, such real time traces contain more information than the power spectrum. By measuring many such traces, we find that the QPC sample stays 8% of the time in low-, 82% of time in the middle-, and 10% of the time in the high-conductance states.

To check whether transitions from one state to another occur randomly, we measured the distribution of transition times. In all cases, we find the measured distribution of transition times to be close to a Poisson distribution. As an example, in Fig. 3 we show the distribution of transition times for the transition from the low-conductance state to the middle-conductance state.

We also measured other QPC samples. In order not to repeat the already known aspects of QPC noise, we will only give here a list of our findings from the QPC samples.

(i) All the QPC samples we measure (around ten samples) exhibit some sort of switching noise with a Lorentzian spectrum. However, the amplitude of switching noise as well as the switching rates are found to be highly sample dependent. We observed switching times ranging from 0.1 ms to 10 s.

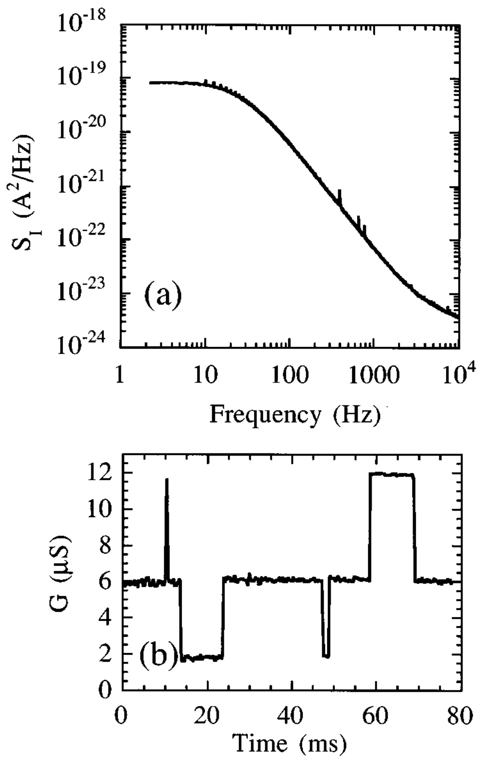

FIG. 2. (a) Current noise power spectrum of a quantum point contact sample after averaging over 10 000 time traces and (b) a typical time trace. Note that the data are converted to conductance G by dividing the measured current by the applied voltage.

(ii) We find that the noise spectra obtained from different cooldowns of the same QPC sample were different. But for a given cooldown of a QPC sample, the noise spectrum remains constant; the three-level switching noise presented above was monitored for three days and no change in switching rates or amplitude was observed.

(iii) Switching noise is also found to be sensitive to illumination by a red light-emitting diode.

(iv) The QPC noise is not limited to two-level switching noise, as we observed a three-level switching noise. The multilevel aspect of the QCP switching sites has not been addressed previously; it is important to note that a theory explaining QPC noise must accommodate the possibility of multilevel switching events.

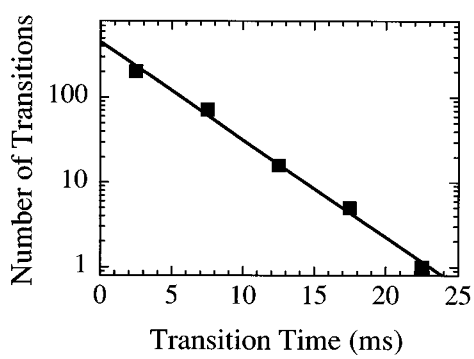

FIG. 3. Distribution of transition times for the transition from the low-conductance state to high-conductance state. A point at time t indicates the number of transitions observed with a transition time within the range $t-2.5$ to $t+2.5$ ms. The solid line is the fit to a Poisson distribution.

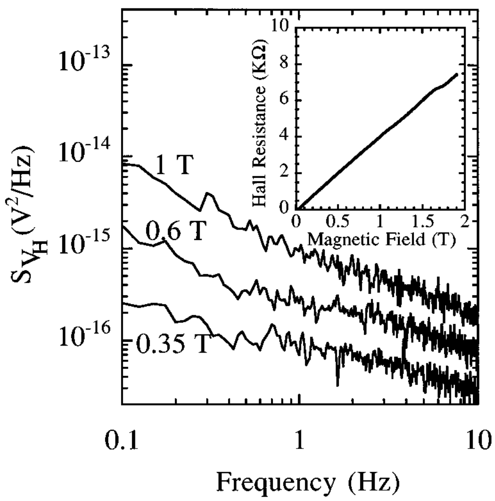

FIG. 4. Hall voltage noise power spectrum for three different magnetic fields: $B=0.35$, 0.6, and 1 T. The inset shows Hall resistance as a function of magnetic field; noise measurements are carried out at the linear regime of the Hall resistance versus magnetic-field curve.

B. Hall bar samples

Noise measurements on Hall bar samples are made using the ac noise measurement of Fig. 1(b). We use a superconducting magnet in persistent mode to maintain constant magnetic fields. Typical Hall voltage noise power spectra $S_{V_H}(f)$ obtained from one of our Hall bar samples are shown for three different magnetic fields in Fig. 4. For this Hall bar structure, the current and voltage leads have widths of 25 and 50 μm, respectively. We limit our noise measurements on Hall voltage to low magnetic fields where the integer quantum Hall effect plateaus do not appear. As shown in the inset of Fig. 4, in this regime the Hall resistance is linearly dependent on the magnetic field.

We find that the noise exponent for $S_{V_H}(f)$ is less than 1 ($\alpha=0.7$). As discussed earlier, such deviations from $1/f$ behavior are observed in many systems and it only implies that the lifetimes of switching events that cause Hall voltage fluctuations are not uniformly distributed in the measurement range of our experiment. Note that increasing the magnetic field causes the whole noise spectrum to increase without changing the noise exponent.

We measured many $S_{V_H}(f)$ similar to the data of Fig. 4, for different currents and magnetic fields. We show $S_{V_H}(f)$ at 1 Hz as a function of B^2 and I^2 in Figs. 5(a) and 5(b). We find $S_{V_H}(f)$ to be quadratic in both B and I; solid lines in Figs. 5(a) and 5(b) show the quadratic fits. This result is not surprising since in our measurement range the Hall voltage is linear in both B and I and $V_H=BI/ne$. On the other hand, this is a very important result, which gives us confidence in deducing information about carrier density fluctuations from $S_{V_H}(f)$.

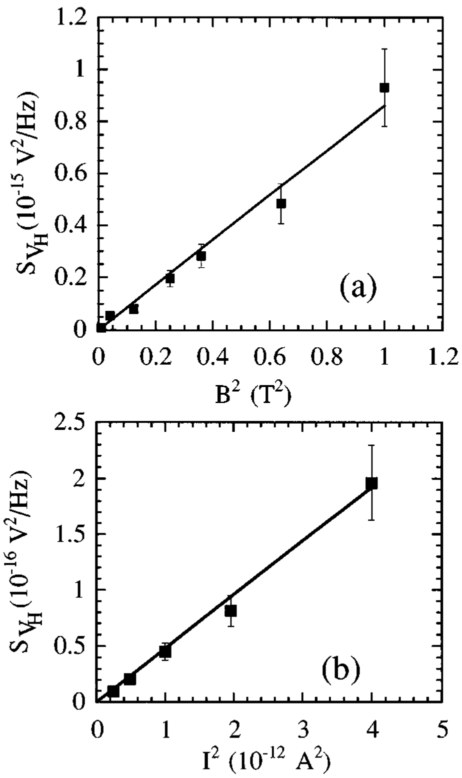

FIG. 5. (a) S_{V_H} (1 Hz) for $I=2$ μA vs B^2 and (b) S_{V_H} (1 Hz) for $B=0.5$ T vs I^2. Solid lines are quadratic fits to the data.

We also measured the voltage along the current flow at zero magnetic field, which we shall refer to as the diagonal voltage using the same setup. Similar to the Hall voltage, the noise spectrum of diagonal voltage is found to be quadratic in current. Using this quadratic dependence, we converted the measured noise power spectrum of the diagonal voltage to a resistance noise spectrum $S_R(f)$ by dividing it by I^2. In Fig. 6 we show $S_R(f)$ obtained from two different sized Hall bar samples. The larger Hall bar sample has a channel length of 400 μm and a channel width of 20 μm, whereas the smaller sample has a channel length of 100 μm and a channel width of 5 μm. $S_R(f)$ of the smaller sample is about 16 times bigger than the larger sample as expected from Hooge's law. This is an experimentally important result in

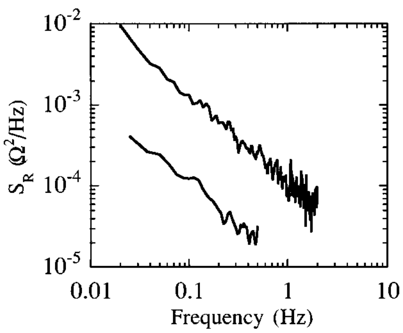

FIG. 6. Resistance noise spectrum of two different Hall bar samples with dimensions 400×20 μm^2 (lower curve) and 100×5 μm^2 (upper curve).

that it further confirms that we are measuring switching events that are happening in the bulk of the sample rather than the contacts.

Finally, we should note that, unlike the noise exponent of $S_{V_H}(f)$, the noise exponent of $S_R(f)$ is equal to 1. The physical origin of the difference in noise exponents is not yet understood.

VI. DISCUSSION AND CONCLUSIONS

We know that in both QPC and Hall bar structures there are switching events that affect the electron system and cause resistance fluctuations. However, we have not yet discussed the underlying physical mechanism of the switching or how these switching events couple to the 2DEG.

As a start, using $E_2-E_1=k_BT\ \ln(\tau_1/\tau_2)$ and the typical transition times of the QPC samples, we estimate the typical energy difference between different switching states to be a few meV. Note that such an energy difference is too small that these switching events cannot be caused by DX centers.

Now let us first consider the density of active switching sites in our GaAs/$Al_xGa_{1-x}As$ heterostructures. By active sites we mean the sites that have switching times that are in the range of our measurements (roughly 1 ms to 100 s). From noise measurements on QPC samples, we know that there are always a few active switching sites that couple to the sample; we have not come across a single QPC sample that was free of switching events. To obtain an order to magnitude estimate for the density of switching sites from the QPC measurements, we estimate the area around the QPC in which a switching site can affect the QPC resistance significantly. In the single-channel limit where we carried out our noise measurements, the channel width is on the order of the Fermi wavelength λ_F. The resistance of a QPC is very sensitive to the electrostatic potential where the channel is narrowest, and to be effective, a switching site should be close to the narrowest point of the channel. We can assume that if the distance between the switching site and the center of the QPC is much larger than λ_F the switching site cannot affect the QPC strongly. There is also recent experimental evidence by Sakamoto, Nakamura, and Nakamura[9] that switching sites are indeed very close to the center of the QPC. In these experiments, noise measurements are carried out on a QPC sample similar to ours, where they shift the QPC channel by applying different gate voltages to the split gate. They were able to scan through seven active switching sites by shifting the channel by 0.27 μm.

Based on these experiments, we can assume that the switching has to be roughly within 1000 Å of the QPC center, which would correspond to an effective QPC area of 10^{-10} cm^2. Now, by assuming one switching site per QPC, we get a switching site density of 10^{10} cm^{-2}. Obviously, this should only be taken as an order of magnitude estimate.

Now we will try to deduce the density of switching sites from the noise measurements on our Hall bar samples. In order to do this, we need to know how the switching events couple to the electron system. There are three ways that switching events couple to the resistance: through carrier density fluctuations, through mobility fluctuations, and through fluctuations in quantum interference corrections. On the other hand, fluctuations in Hall voltage are not affected by mobility fluctuations and carrier density fluctuations alone would lead to a quadratic B dependence. Thus we will use S_{V_H} to extract information about carrier density fluctuations. To proceed, we have to know the impact of a typical switching event on the carriers in the sample. If a typical switching event is electron trapping, it would modulate the total number of electrons by 1. On the other hand, a remote event that is weakly coupled to the electron system can modulate the total number of electrons by much less than 1.

Let us first assume that each switching event is strongly coupled to the 2DEG and, as in the case of electron trapping, modulate the total number of electrons by 1. Now we can infer the density of switching sites from Hall voltage fluctuations using standard arguments. For a macroscopic Hall bar sample with N electrons and N_{SS} uncorrelated switching sites ($N=An$ and $N_{SS}=An_{SS}$, where A is the area of the sample), the fluctuation in the total number of electrons ΔN would be given by $\Delta N=\sqrt{N_{SS}}$. The fluctuations in Hall voltage are directly related to the fluctuations in the total number of carriers, $\Delta V_H/V_H=\Delta N/N$. For our Hall bar samples, we determine ΔV_H by integrating S_{V_H} and obtain $n_{SS}\approx 10^8\ \mathrm{cm}^{-2}$.

Since this n_{SS} obtained from Hall voltage measurements and based on the assumption of strong coupling is two orders of magnitude smaller than our estimate of n_{SS} from QPC measurements, we can conclude that the electron trapping is not the main switching event in Hall bar samples. In other words, to have consistency between Hall bar and QPC measurements, the majority of the switching events must have less impact than electron trapping on Hall voltage. In fact, by using our estimate of $n_{SS}=10^{10}\ \mathrm{cm}^{-2}$ we can deduce that a typical switching site would modulate the total number of electrons of the sample by a small amount (≈ 0.1).

Furthermore, from QPC measurements, we know that a switching site can have more than two states and typically the states of a switching site are nearly degenerate in energy. The only mechanism that can accommodate all these observations is fluctuation in the remote impurity configuration of the selectively doped GaAs/Al_xGa_{1-x}As heterostructure. To have a microscopic theory of the resistance fluctuations, we need to be able to calculate resistance of a sample with a realistic impurity configuration and know how the remote impurity configuration changes in time. For some structures, such as QPC's, we can calculate resistance of a sample for a given impurity configuration,[17,18] but we do not yet know how to calculate the dynamics of the remote impurity configuration.

In conclusion, we studied resistance fluctuations in GaAs/Al_xGa_{1-x}As QPC and Hall bar structures. combining measurements from these two sets of samples, we identified the physical origin of resistance fluctuations in this system as fluctuations in the remote impurity configuration. We find that there are approximately $10^{10}\ \mathrm{cm}^{-2}$ such active fluctuation sites in our sample and each site on the average modulates the total number of electrons in the sample by 0.1. We also find that an active impurity can have more than two states leading to the multilevel switching observed in our QPC samples.

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