Modulation of Noise in Submicron GaAs/AlGaAs Hall Devices by Gating

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We present a systematic characterization of fluctuations in submicron Hall devices based on GaAs/AlGaAs two-dimensional electron gas heterostructures at temperatures between 1.5 to 60 K. A large variety of noise spectra, from $1/f$ to Lorentzian, are obtained by gating the Hall devices. The noise level can be reduced by up to several orders of magnitude with a moderate gate voltage of 0.2 V, whereas the carrier density increases less than 60% in the same range. The significant dependence of the Hall noise spectra on temperature and gate voltage is explained in terms of the switching processes related to impurities in n-AlGaAs.

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Developing high-sensitivity noninvasive techniques for nanoscale magnetic measurement is one of the great challenges in nanoscience today. Extensive effort has been made to improve the sensitivity of magnetometers for *single* nanoparticle measurements by miniaturizing the detecting devices to micron and even nanometer scale, such as a micrometer sized SQUID loop [1], a micro-cantilever [2], and a submicron semiconductor Hall gradiometer [3]. Among these techniques, Hall magnetometers based on two-dimensional gas (2DEG) III/V semiconductor heterostructures have many advantages over other techniques such as wide range of operational temperature and applied field [4]. We have recently demonstrated a moment sensitivity of $\sim 10^5\ \mu_B$ in a large perpendicular field by measuring a single Fe nanoparticle with a submicron GaAs/AlGaAs Hall magnetometer [3]. Further miniaturization should increase the average stray field of the magnetic nanoparticle and result in even higher sensitivity, if the noise can be maintained at low level. Unfortunately, miniaturization is also expected to increase the noise level, especially $1/f$ noise at low frequencies. Therefore, a detailed understanding of sources of noise is critical in improving device performance.

There exists a long history of noise studies in a variety of GaAs/AlGaAs 2DEG devices. These include *resistance* fluctuations in quantum point contacts (QPC) confined by the split-gate technique [5–9] as well as macroscopic scale devices [9,10]. Several mechanisms have been proposed to account for the observed $1/f$ noise and Lorentzian noise, including electron trapping [5], switching in remote impurities [6,9,11], electron screening effect [12], and DX centers (deep donor levels) [8,13]. No definitive conclusions have, however, been reached. Surprisingly, there are few studies of the Hall voltage noise in GaAs/Al_xGa_{1-x}As 2DEGs, especially at temperatures below 77 K at which these Hall devices have the best performance. To the best of our knowledge, in this temperature range, there was only one report on Hall voltage noise of (large) $25 \times 50\ \mu m^2$ Hall bars at 4.2 K [9]. In submicron 2DEG devices, various mesoscopic effects proliferate, leading to transport properties considerably different from macroscopic ones. Although the work on QPC samples at low temperatures has given much insight into this problem, direct measurement of fluctuations in submicron Hall devices may provide us further in-depth understanding of the dynamic aspect of transport properties.

In this Letter, we report the first detailed measurement of low frequency Hall-effect noise in submicron GaAs/AlGaAs 2DEG devices at temperatures between 1.5 and 60 K. We observed a pronounced dependence of both the type and the magnitude of the noise on temperature and gating. In particular, we discovered that a significant suppression of the noise can be achieved with moderate gate voltage.

The GaAs/Al_xGa_{1-x}As heterostructure used in this study was grown on an undoped GaAs substrate and consists of a 1000 nm thick undoped GaAs buffer layer, a 30 nm thick undoped $Al_{0.29}Ga_{0.71}$As spacer layer, a 100 nm thick Si doped $Al_{0.29}Ga_{0.71}$As layer with a dopant density of 10^{18} cm^{-3}, and a 10 nm thick GaAs cap layer. The electron density and Hall mobility of this wafer were determined to be $n \simeq 1.5 \times 10^{11}$ cm^{-2} and $\mu_H \simeq 10^5$ cm^2/Vs at $T \leq 77$ K, respectively. Submicron Hall bar patterns were fabricated by electron beam lithography followed by wet etching. The sample used for noise measurements to be presented here has three Hall crosses of $0.7 \times 0.7\ \mu m^2$ with an etching depth of 70 nm and a 50 nm thick Au/Cr gate deposited on top. The carrier concentration at zero gate voltage ($V_G = 0$) determined from the Hall measurements is $\sim 1.2 \times 10^{11}$ cm^{-2}, and varies by less than 1% for $T \leq 75\ K$. Similar results have been observed on a number of samples having various geometries fabricated from the same wafer [14] and different wafers with similar GaAs/AlGaAs heterostructures [15].

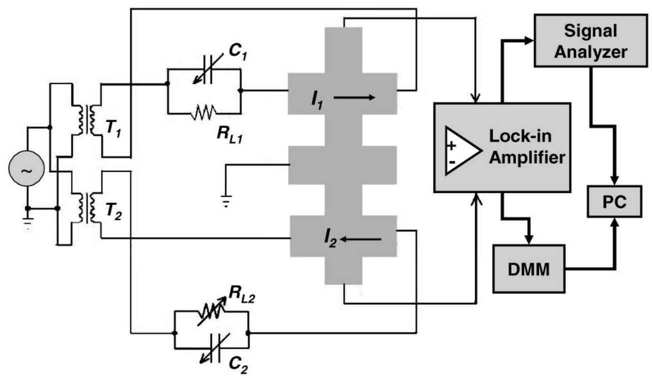

FIG. 1. The seven-terminal gradiometry circuit for ac Hall-effect noise measurements.

A 7-terminal ac gradiometry setup shown in Fig. 1 was used for the noise measurement. The two currents I_1 and I_2 applied to Hall crosses 1 and 2 are supplied from two identical transformers, which have common input from a function generator. Both the amplitude and the phase of I_1 and I_2 can be balanced by limiting resistors and shunt capacitors to ensure that the output ΔV_H of the Hall gradiometer has a zero offset. This design was adapted from a 5-terminal ac circuit for measuring resistance fluctuations [16]. The unique feature of the present design is that the balancing circuit is provided by passive elements, and the symmetry ensures less vulnerability to external fluctuations. However, the measured noise power spectral density (PSD) is $S_{VH} = S_{VH1} + S_{VH2}$, where S_{VH1} and S_{VH2} are the PSD of Hall cross 1 and 2, respectively. The output signal of a lock-in amplifier (PAR 124A or EG&G 5301) operating at frequency $f_c \sim 517$ Hz in bandpass mode ($Q = 1$) was processed into a spectrum analyzer. We used a superconducting magnet in persistent mode to maintain a constant field perpendicular to the 2DEG plane. All spurious sources of noise, especially those coming from the gate itself could be ruled out or eliminated.

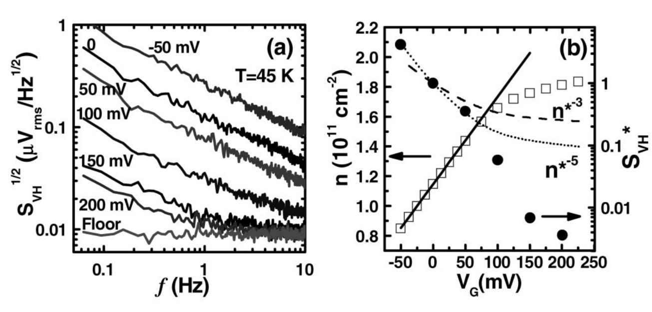

FIG. 2. (a) Gate voltage dependence of noise spectra at $T = 45$ K and $B = 0.5$ T taken with $I \sim 1$ μA. (b) Gate voltage dependence of carrier concentration (open squares) and the scaled noise power spectrum density $S^*_{VH} = S_{VH}(V_G)/S_{VH}(V_G = 0)$ at 1 Hz (solid circles). n^* is the relative change in carrier density, defined as $n^* = n(V_G)/n(V_G = 0)$.

At $V_G = 0$, the noise has $1/f^\alpha$-like spectra with $\alpha = 1.0 \pm 0.1$ at $T = 15$ to 60 K in an applied field up to at least $B = 1$ T. In all cases, the PSD at 1 Hz scales with I^2 as expected. Furthermore, the normalized $S_{RH} = S_{VH}/I^2$ has a linear B^2 dependence at all temperatures. Although the quadratic dependence for the Hall-effect noise was predicted and observed for high mobility samples ($\mu_H B \gg 1$) in the diffusive regime [17], it is surprising that it is followed so well in our samples where ballistic transport is not negligible.

The most dramatic observations occurred when a gate voltage was applied to the device. Although the exact gate voltage dependence varies at different temperatures, *with* $V_G = 0.2$ V *the noise level was suppressed by more than two orders magnitude in the entire temperature range* (5–60 K). The gating behavior is straightforward at high temperatures. For example, at $T = 45$ K, S_{VH} is consistently suppressed while maintaining the $1/f$ characteristic, as shown in Fig. 2(a). At $V_G = 0.2$ V, the noise level is almost reduced to the background noise level at high frequencies. The relative reduction in S_{VH}, $S^*_{VH} = S_{VH}(V_G)/S_{VH}(V_G = 0)$, at different gate voltages, is plotted in Fig. 2(b), which exhibits a decrease of a factor of $\sim$300 from $V_G = 0$ to 0.2 V. This reduction is much greater than what is expected from the increase in carrier density with gating. A n^{-3} dependence is expected from Hooge's empirical rule, i.e., $S_{VH} = \frac{\alpha_H}{N f^\alpha} V_H^2 \propto n^{-3}$, where N is the total carrier number in the device, and α_H is the Hooge's constant. The measured change in carrier density n of $\sim$60% from $V_G = 0$ to 0.2 V should yield only a factor 4 decrease in S_{VH}, which clearly contradicts our results. Similar gate voltage dependencies have been observed at fields from $B = 0.25$ T to 1 T. The unexpected rapid decrease in S_{VH} with V_G is of great practical importance, since the quantity S_{VH}/V_H^2 will determine the ultimate field sensitivity of the Hall device. We point out that the noise level for a 0.7×0.7 μm^2 Hall cross at $T = 45$ K, $B = 0.5$ T, and $V_G = 0.2$ V is only $S_{RH}/2 = 2.5 \times 10^{-5}$ Ω^2/Hz at 1 Hz, which is even smaller than an ungated macroscopic sample at $T = 4.2$ K [9].

The gate voltage dependence of S_{VH} at low temperatures is considerably more complex than that at $T = 45$ K. Figures 3(a) and 3(b) show the results at $T = 15$ K. Initially ($V_G \leq 75$ mV), an *increase* in noise level and deviation from $1/f$ spectra are observed with increasing V_G. Further increase in V_G results in a rapid reduction in noise level and restoration of $1/f$ spectra. The complex behavior at low temperature cannot be explained simply by changes in carrier density or mobility since both quantities remain relatively constant below 60 K. At $V_G = 75$ mV, the noise reaches the highest level and the spectra are more Lorentzian like than $1/f$, concomitant with the approach to saturation of n at $V_G > 0.1$ V [Fig. 2(b)]. Such a transition from linear dependence to saturation for n has been observed and explained by

Hirakawa *et al.* [18], who noted that when V_G is smaller than a certain threshold voltage (~75 mV in this case), the quasi-Fermi level in n-doped AlGaAs is lower than the donor level, the Si donors are fully depleted, and the gated 2DEG structure acts like a parallel plate capacitor, resulting in the linear dependence of carrier concentration on V_G. However, for larger values of V_G, the quasi-Fermi level passes through the donor level, and a neutral region forms in the n-AlGaAs layer, which leads to the saturation effect. The coincidence of the highest noise level and the appearance of Lorentzian behavior with the beginning of the formation of the neutral layer strongly suggests that the switching processes related to donors in n-AlGaAs may be responsible for the pronounced and complex gate voltage dependence of fluctuations. Furthermore, the noise can be reduced by the shielding effect of the neutral layer at higher V_G if the fluctuations are related to the impurities in n-AlGaAs. The key question is: how does one explain the dramatically different gating behavior at different temperatures?

Figure 4(a) shows the noise spectra taken at $V_G = 75$ mV and $T = 13$ to 35 K. With decreases in temperature, the noise level increases rapidly and the deviation from $1/f$ becomes clear. At higher temperatures, the noise spectra are $1/f$-like at lower frequencies, but become flat at higher frequencies. At $T = 20$ K, the local spectral slope, defined as $\nu(f) \equiv -\partial \ln S_V H(f)/\partial \ln f$, remains a value less than 1 over the entire measured frequency range (0.01–25 Hz). For the spectra at $T = 13$–17 K, $\nu(f)$ varies monotonically from less than 1 to larger than 1. We can therefore use the characteristic frequencies f_p, at which $\nu(f) = 1$, to extract the peak activation energy E_p. Fitting the data to an Arrhenius law $f_p = f_0 \exp(-\frac{E_p}{k_B T})$, we obtain $E_p = 27 \pm 3$ meV and attempt frequency $f_0 = 10^8$–10^9 Hz, which is about the same as that obtained from the telegraph noise measurements on the GaAs/AlGaAs 2DEG QPC samples ($f_0 \sim 10^9$ Hz) [5]. The Gaussian spreading width of the activation energy distribution around E_p obtained from $T = 13$–20 K data is about 8 meV, based on the Dutta-Horn approach [19]. This narrow distribution in E_a gives rise to Lorentzian type of spectra ($S_{VL}(f) = S_{VL}^0/(1 + 4\pi^2 f^2 \tau^2)$ with $S_{VL}^0 \propto \tau = \tau_0 \exp(E_a/k_B T)$ and $\tau_0 \sim f_0^{-1}$) which dominate at lower temperatures. At higher temperatures, the corner frequency $f_c(\sim\tau^{-1})$ becomes much larger than 25 Hz, so the observed noise spectra can be approximately decomposed as: $S_{VH}(f) = \frac{S_{VH}^0}{f} + S_{VL}^0$, where the first term is the $1/f$ component corresponding to a uniform distribution in activation energy E_a, and $S_{VL}^0 \propto \tau$ is the flat part ($f \ll f_c$) of the Lorentzian spectrum. The strong temperature dependence of τ can explain the rapid increase in the noise level in a narrow temperature range (35 to 20 K). As shown in Fig. 4(c), the $\log(S_{VL}^0)$-$1/T$ fit for data at $T = 22$–35 K yields $E_a = 24$ meV, which is reasonably close to the $E_p \simeq 27$ meV obtained from the $T = 13$–17 K data. The overall feature of the noise spectra at $V_G = 100$ mV, shown in Fig. 4(b), is similar to that at $V_G = 75$ mV, but the noise level is lower. With a similar $\log(S_{VL}^0)$-$1/T$ fit at temperatures between 21 and 45 K, we obtain $E_a \simeq 12$ meV [Fig. 4(c)]. At temperatures below 6 K, the noise spectra stop changing with

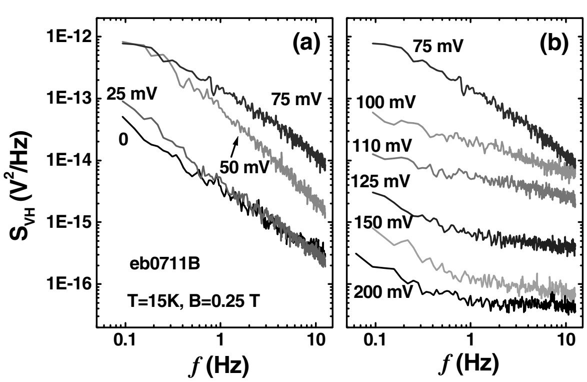

FIG. 3. Gate voltage dependence of noise spectra at $T = 15$ K and $B = 0.25$ T taken with $I \simeq 1.45$ μA. (a) Noise level increases with increasing gate voltage at $V_G \leq 75$ mV. (b) Noise level decreases rapidly as V_G increases beyond 75 mV.

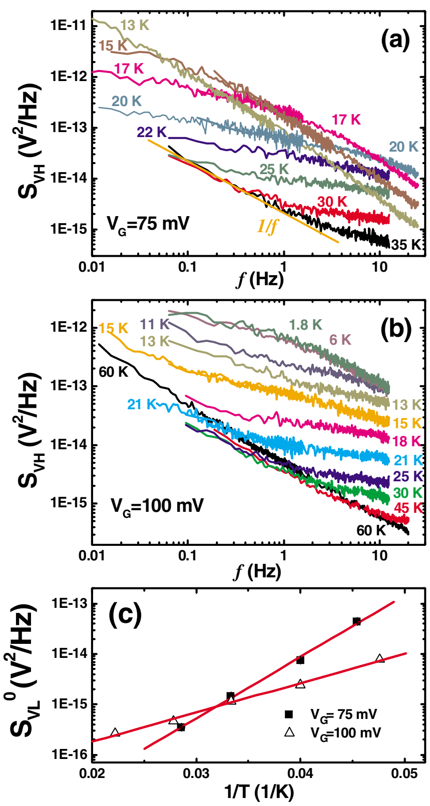

FIG. 4 (color online). Temperature dependence of noise spectra at (a) $V_G = 75$ mV and (b) $V_G = 100$ mV; (c) shows the $\log(S_{VL}^0) - 1/T$ fits for these two gate voltages.

temperature, which can be explained by a crossover from thermal activation to quantum tunneling [5].

So far, we have seen that the large temperature dependence of the noise spectra at intermediate gate voltages can be attributed to the thermally activated process related to a narrow distribution in the activation energy E_a. The gate voltage dependence of the carrier density indicates that the ionized impurities in n-AlGaAs start to capture electrons noticeably at $V_G \sim 75$ mV and form a neutral layer at higher V_G. However, at $V_G \leq 0.1$ V, the occupied impurity density is so low that the n-AlGaAs is still insulating and its transport is via electron hopping between localized states. The energy barrier for the thermally activated hopping is dependent on the overlapping of the corresponding wave functions. This can explain why the extracted activation energy from the noise spectra decreases as the gate voltage increases. The latter increases the neutral impurity density, and hence the overlap of the localized electron wave functions also becomes larger. The large gate voltage dependence of the noise spectra, therefore, can be attributed to the change of the thermal activation energy as well as the neutral impurity density with the gate voltage.

In contrast to the noise spectra at intermediate gate voltages, the noise at $V_G = 0$ and 0.2 V has a $1/f$-like spectrum over the entire temperature range (15–60 K). The frequency exponent for each spectrum was found to be close to 1 ($0.9 < \alpha < 1.1$). The noise level increases with temperature, which is expected for the thermally activated switching process [19]. At $V_G = 0.2$ V and $T =$ 15–60 K, S_{VH} maintains scaling with I^2 up to very large currents ($I \simeq 6$ μA), which is surprising because considerable electron heating effect (tens of Kelvins) has been observed from transport measurements, such as longitudinal magnetoresistance and small nonlinear component of the Hall voltages [14]. This indicates that the noise is almost independent of the electron temperature in our experimental range, which rules out the possibility that the dominating noise observed in this work comes from any effect related to the 2DEG alone, such as the electron-electron interaction. On the other hand, the strong dependence of the noise on the lattice temperature further supports the picture that the observed noise originates from the remote impurities in n-AlGaAs. Similar gating effects have been observed in resistance fluctuation measurements without magnetic field applied, providing further validation of the proposed noise mechanism based on the Hall noise measurements discussed above.

In summary, we have shown that submicron Hall devices combined with gating are excellent probes to study the fluctuations in GaAs/AlGaAs 2DEG heterostructures. The detailed study of the noise has shown that the large gate voltage dependence cannot be explained by changes in the electron density or mobility. The data suggest that the thermally activated switching processes related to remote impurities are responsible for the observed noise behavior. Most importantly, we have found that suppression of noise up to a few orders of magnitude can be achieved by moderate gating over the entire temperature range (5–60 K), which is of great importance for device applications. In fact, the gating effect has been utilized for the measurements of individual magnetic nanoparticles with moment sensitivity better than $\sim 10^4$ $\mu_B/\sqrt{\text{Hz}}$ at 1 Hz and $T = 15$ K and a perpendicular applied field $B = 0.25$ T [14].

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