Stochastic Resonance in Schottky Wrap Gate-controlled GaAs Nanowire Field Effect Transistors and Their Networks

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Investigation of stochastic resonance in GaAs-based nanowire field-effect transistors (FETs) controlled by Schottky wrap gate and their networks is described. When a weak pulse train is given to the gate of the FET operating in a subthreshold region, the correlation between the input-pulse and source-drain current increases by adding input noise. Enhancement of the correlation is observed in a summing network of the FETs. Measured correlation coefficient of the present system can be larger than that in a linear system in the wide range of noise. An analytical model based on the electron motion over a gate-induced potential barrier quantitatively explains the experimental behaviors.

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Stochastic resonance (SR) is an unique phenomenon in which a weak-signal response is enhanced by adding noise[1,2]. The phenomenon has been found to play important roles in biological systems [3-5]. It is also known to occur artificially in various electronic systems, for example, Schmitt trigger circuits[6], pn-junction diodes[7], Josephson junctions[8], carbon nanotubes[9], and single electron devices[10]. Engineering applications of the phenomenon has been investigated, such as weak-signal detection[11], image perception[12], and bio-inspired signal processing[13]. However, there has been no suitable electronic system for the applications, in which small size, easiness of fabrication and integration, room temperature operation, and compatibility to previous systems are necessary. Meanwhile, an emerging issue for modern logic large-scale integrated circuits (LSIs) having a nanometer-scale architecture is to adapt them to fluctuation. Miniaturized transistors in current Si complementary metal-oxide-semiconductor (CMOS) LSIs are affected greatly by fluctuations such as threshold voltage, lithography patterns, dopant position, and signal noise[14-16]. These fluctuations are obviously inevitable when there are over a billion transistors on a semiconductor chip. The problem is more serious in emerging materials and devices for future LSIs including carbon nanotubes, semiconductor nanowires, and single electron devices. However, biological systems having a molecular-scale architecture can operate robustly even with fluctuations in a noisy environment. The SR has been discussed for its key mechanism[5,17,18]. It is pointed out to improve the response of the system affected not only by noise but also by threshold variation[19]. These facts indicate that the SR provides a potential solution for threshold voltage and other variations in nanometer-scale devices. Based on the background mentioned above, in this paper, we investigate the stochastic resonance behavior of electrons in GaAs-based nanowire field effect transistors (FETs) controlled by Schottky wrap gate (WPG) and their network experimentally. A physical model is introduced for quantitative analysis of the observed behaviors. We study a semiconductor nanowire FET in this letter, since it is

expected to play important roles in the next generation nanolelectronics.[14] There is a strong demand for robustness against fluctuations, because the nanowire is sensitive to various fluctuations. Moreover, the nanowire is suitable to form physical network structure, in which the SR phenomenon is enhanced [19]. This would also provide an opportunity to utilize bottom-up nanotechnology, where high-density network or bundle structures are easily produced in low cost even with some physical fluctuations.

Figure 1(a) is a schematic of the system studied in this letter. Each FET has a GaAs-based nanowire channel and a Schottky wrap gate (WPG), which is shown in Fig. 1(b). The nanowire was formed by electron beam lithography and etching of a conventional AlGaAs/GaAs modulation-doped heterostructure. A parallel FET network simulates the summing network of sensory neurons [19], improving the signal-to-noise ratio even with variation of threshold in the elements. A common voltage pulse train is given to gates of all the FETs as an input signal. The summed source-drain current, I_{out}, is monitored as output through a summer circuit. Uncorrelated noise is added to each gate input. Here, the gate voltage, V_G, is biased less than the threshold voltage, V_{th}, so that FETs operate in the subthreshold region.

A fabricated FET device had a nanowire with a width, W, of 550 nm and a WPG gate length, L_G, of 640 nm. The mobility of a two-dimensional electron gas (2DEG), μ_e, was 7,000 cm^2/Vs, and its sheet carrier density, n_s, was 1.0 x 10^{12} cm^{-2} at room temperature (RT). The evaluated mean free path was 70 nm, which was shorter than the gate length. The V_G dependence of the source-drain current in the FET is shown in Fig. 1(c). A small source-drain voltage, V_{DS}, of 0.1 V was used to avoid the drain induced barrier lowering. The measured V_{th} was -1.0 V, and the subthreshold slope, S, was 89 mV at RT. The input pulse train and voltage noise were generated by conventional digital signal synthesizers. The generated noise was a Gaussian white noise with a bandwidth of 50 kHz. The output waveforms were measured

using a digital oscilloscope. In this study, the N-parallel network with uncorrelated noise was virtually reproduced by dividing a sampled waveform from a single FET into N pieces and summing them. All the measurements were carried out at RT.

An example of measured waveforms is shown in Fig. 1(d) for $N = 1$. The measurement was performed at the input-pulse height, ΔV_{in}, of 0.02 V and the duty ratio, γ, of 20%. The pulse frequency, Ω, was 100 Hz, significantly lower than the bandwidth of the noise. The gate was biased at V_{offset} = -1.5 V. This value was much smaller than V_{th}, and the input never reached V_{th} without noise. The noise intensity was measured by the root mean square (rms) of the generated noise voltage, V_{noise}. The waveforms in Fig. 1(d) were taken at V_{noise} = 0.035 V. As this figure shows, finding the pulse train is quite difficult because of the noise-added input. However, the output from the FET exhibited some response that was correlated with the input-pulse train.

The correlation between the input and the output waveforms was measured using the correlation coefficient, C_1, given by

$$C_1 = \frac{\langle V_{in} \cdot I_{out} \rangle - \langle V_{in} \rangle \langle I_{out} \rangle}{\sqrt{\langle V_{in}{}^2 \rangle - \langle V_{in} \rangle^2} \sqrt{\langle I_{out}{}^2 \rangle - \langle I_{out} \rangle^2}}, \qquad (1)$$

where $\langle V_{in} \rangle$ denotes the ensemble average of $V_{in}(t)$. The measured correlation coefficients are plotted as a function of noise voltage in Fig. 2, for $N = 1$, 2, and 8. In this plot, the ΔV_{in} was 0.02 V, and the V_{offset} was -1.4 V. The other parameters were the same as those in Fig. 1(d). C_1 for the present system peaked, indicating the appearance of the stochastic resonance. The peak position for $N = 1$ was 0.035 V. For comparison, the measured C_1 for a linear system with N-time averaging, in which the output was given by the sum of the input and noise, is also plotted in Fig. 2 by dashed lines. It shows that the correlation decreased monotonically as the noise increased. Theoretical value of C_1 for the linear system is given by $1/[1+(V_{noise}/\gamma\Delta V_{in})^2/N]^{1/2}$, and it explains the measured curves well. The correlation in our

system was significantly larger than that in the linear system in the wide range of noise. Moreover, the correlation increased as more paralleled devices were used. C_1 = 0.41 was obtained in the present system for N = 8, which was 40% larger than that in the linear system at the same noise voltage. The measured peak positions did not depend on N. These results were similar to the behaviors in the summing network of sensory neurons reported by Collins *et al* [19].

To clarify the obtained results, we conducted a theoretical analysis using the physical model shown in Fig. 3(a). In the subthreshold region of a FET, the gate induces an electrostatic potential barrier with a height of ΔU. Noise in the source-gate voltage fluctuates the potential barrier. Some electrons that have energy exceeding the fluctuated barrier can move to the drain, even though the input pulse itself cannot sufficiently decrease it. This results in the source-drain current. From the drift motion of electrons in the semiconductor, a Langevin equation was deduced, such as $\partial x(t)/\partial t = \mu_e[-\partial V(x,t)/\partial x + \xi(t)]$, where $V(x,t)$ is the electric potential, and $\xi(t)$ is random force. $1/\mu_e$ corresponds to the viscosity of this system. We assumed that the rate of electrons surmounting the potential barrier was given by Kramers rate [1)], k_r, and that the potential around the barrier was quartic. By computing eq. (1) for the motion of electrons described by the Langevin equation assuming a sinusoidal input for simplicity, we obtain an analytical formula of the correlation coefficient by the next formula,

$$C_1 = \frac{1}{\sqrt{1 + K\left(V_{noise}/\gamma\Delta V_{in}\right)^2/N}} \frac{1}{\sqrt{1 + \left(\Omega/2k_r\right)^2}}, \qquad (2)$$

where $k_r = 4\mu_e\alpha\Delta V_G/L_G^2 \exp(-2\Delta V_G/V_{noise})$, α is gate voltage to energy scaling factor, $\Delta V_G = V_{th} - V_{offset}$, and K is an empirical parameter coming from the time-dependent fluctuation of Kramers rate due to noise in the input [20)]. ΔU is evaluated by $\alpha\Delta V_G$. α was estimated to be 0.68 from the measured subthreshold slope using $1/\alpha = S/[kT \ln(10)/e]$. The peak height and position can be evaluated from eq. (2). It shows that the peak position can be shifted

artificially by changing the gate voltage, which has been confirmed experimentally and will be shown elsewhere. It also predicts that the response speed is increased by increasing the carrier mobility and by reducing the gate length.

Calculated correlation coefficients using eq. (2) are shown in Fig. 3(b) together with the experimental data. The theory exhibited a peak at V_{noise} = 0.04 V, and it reproduced experimentally observed behaviors well, including peak position, height, and N-dependence. Here, we only assumed K = 0.5 and known values were used for other parameters. However, the experimental data showed broader tails in the low noise region compared with the theory. In addition, the correlation in V_{noise} > 0.04 V was weaker than the theory for N = 1. These discrepancies were understood by the effect of unintentional noise, which was in the order of 1 mV rms in the measurement setup. Namely, external and internal noise that was added to the input effectively increased V_{noise}. This should cause the tail of the peak in the low noise region. On the other hand, noise in the output cables and equipment degraded the output signal, resulting in the decrease in the correlation coefficient. This would be prominent when the output was small, such as N = 1, or for the data in the high noise region.

The quantitative effect of the formation of networks can be seen from the correlation coefficients for large N values that were calculated using eq. (2). These correlations are plotted in Fig. 3(b). As N increases, the peak becomes higher and wider. C_1 as a function of N at the peak is shown in Fig. 3(c), together with the correlations for the linear system. Strong correlation exceeding 0.7 was found when N = 48 in our system, whereas the linear system required N = 97. These trends suggested that the performance of our system was twice that of the linear system. In addition, eq. (2) shows that K is an important parameter in our system. It should be larger than 0 theoretically, corresponding to no fluctuation of the output even with the fluctuated input. On the other hand, K = 1 corresponds to averaging in the linear system. A smaller K results in a stronger input-output correlation and K < 1 is necessary to ensure our

system's advantage over the linear system. Taking account of these conditions, we found K = 0.5 for the present system. Recently, we also measured another device and it indicated that K depends on the system such has the nonlinearity, however, it has not been clarified yet. In order to determine K as well as to verify the validity of the obtained value of 0.5, it is necessary to evaluate K in devices with different gate control characteristics and correlation between them. These are now under investigation.

In conclusion, the stochastic resonance behavior of electrons was observed in GaAs-based nanowire FETs with WPGs operating in the subthreshold region. The input-output correlation was found to increase in the FET summing network. The observed behaviors could be explained quantitatively using a physical model based on the electron motion over the electrostatic barrier in the nanowire channel induced by the gate.

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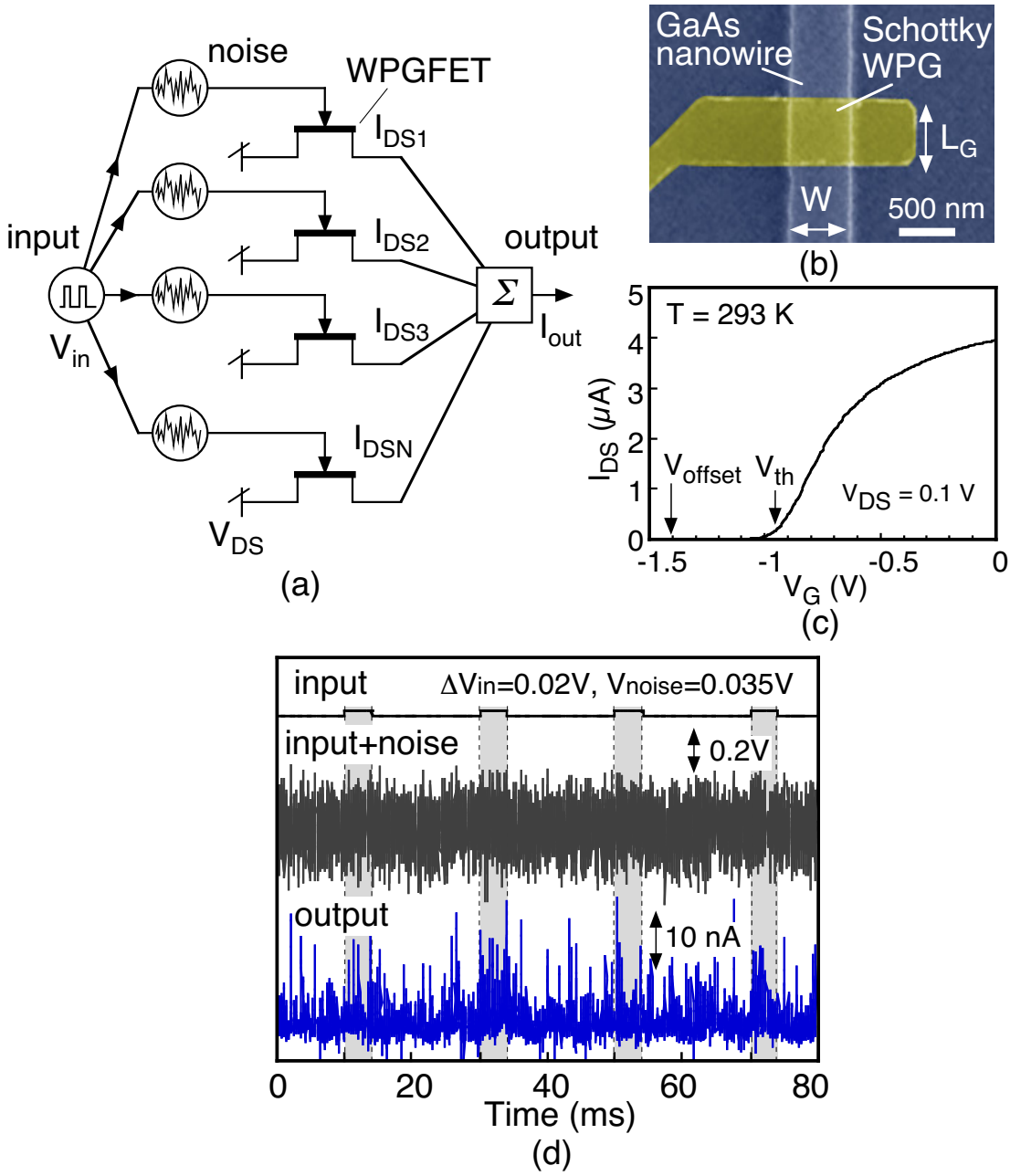
Figure captions

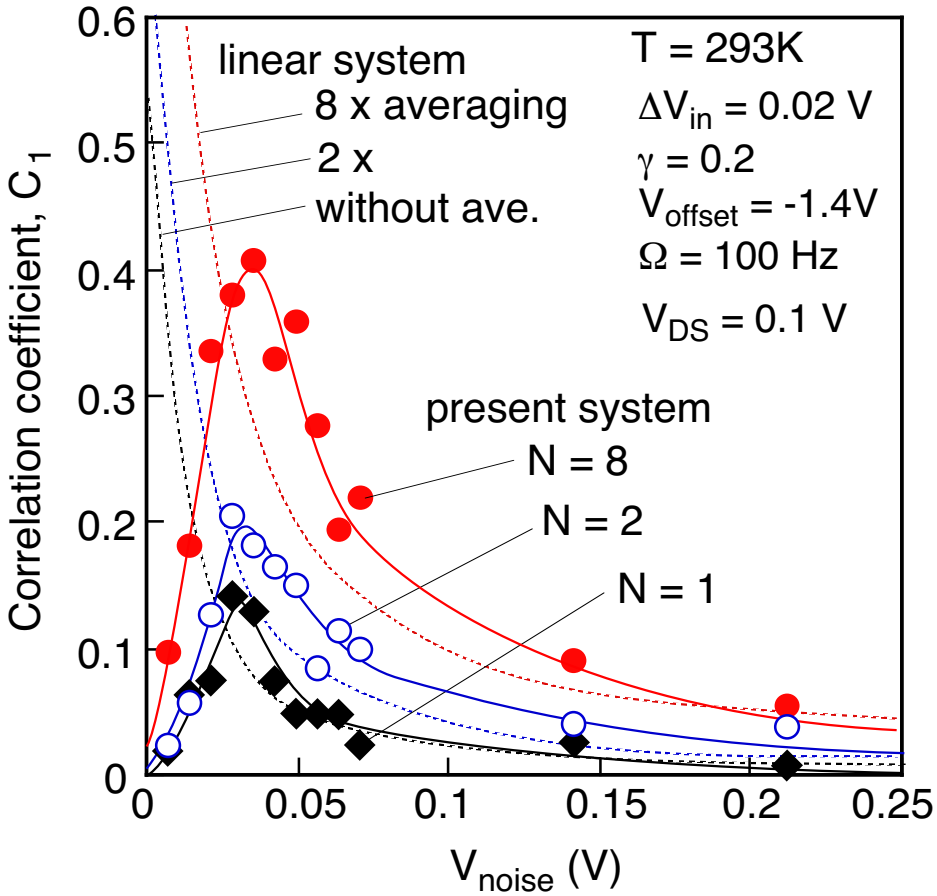
Fig. 1 (a) FET network, (b) scanning electron microscope (SEM) image of WPG FET, (c) measured I_{DS}-V_G curve, and (d) example of input and output waveforms.

Fig. 2 Measured correlation coefficients as a function of noise voltage, V_{noise}, for present and linear systems. Solid lines indicate eye-guides.

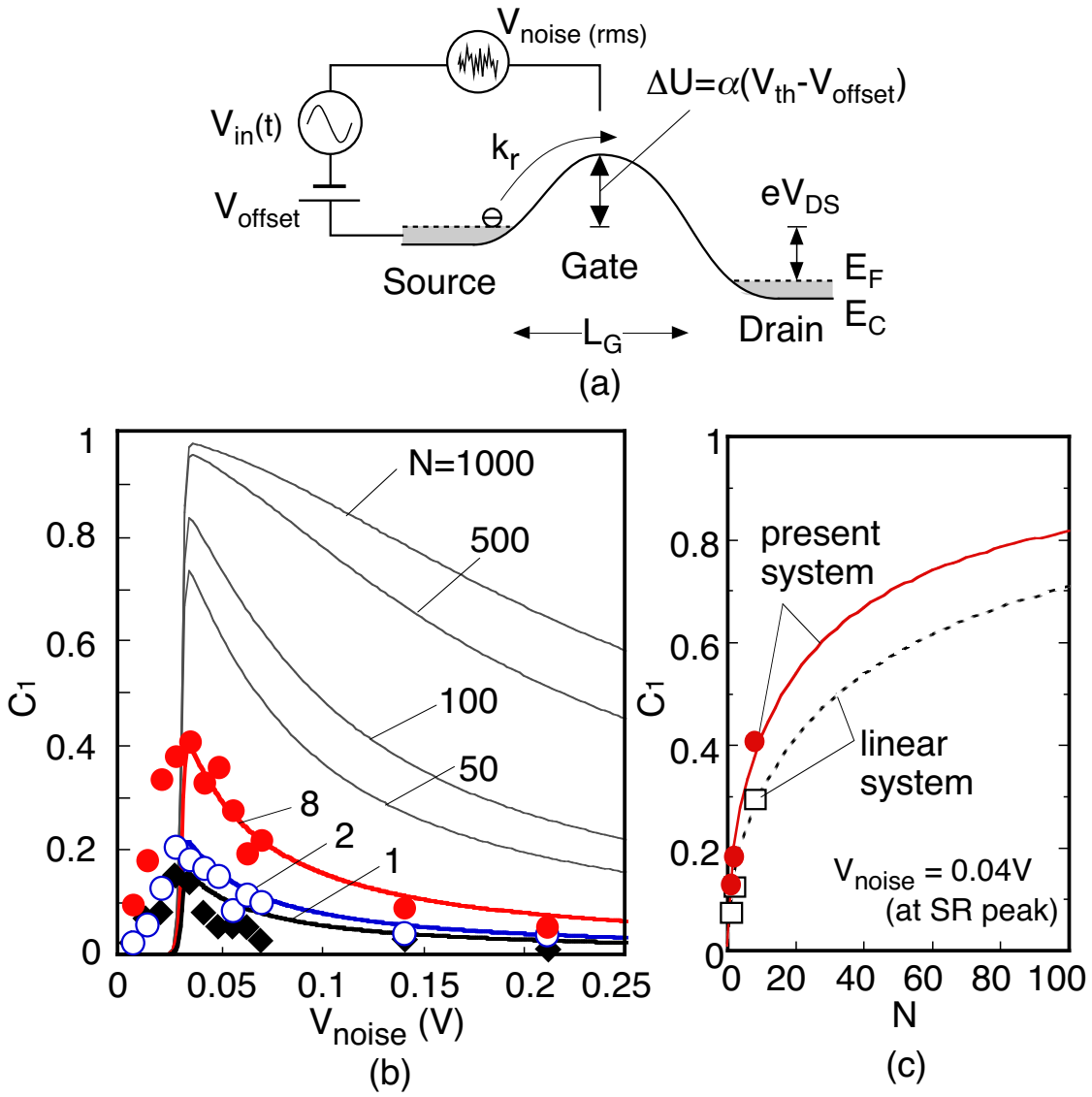
Fig. 3 (a) Physical model for electron motion in subthreshold region and calculated correlation coefficients as a function of (b) noise voltage, V_{noise}, and (c) number of integrated devices in parallel, N. Circle and square symbols indicate experimental data.



Kasai et al., Figure 1



Kasai et al., Figure 2



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