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Low-Frequency Noise Characteristics of AlGaAs/InGaAs Pseudomorphic HEMTs

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SUMMARY The low-frequency noise of InGaAs pseudomorphic HEMTs fabricated on GaAs substrate was studied. The dependence of the noise spectral density on the gate voltage indicates that the channel of the device dominates the low-frequency noise. Generation-recombination (G-R) noise was observed in the form of bulges superimposed on a background of 1/f. The activation energyof the G-R noise was 0.32–0.39 eV which is close to that of the DX center, suggesting that the origin of the G-R noise is the DX center in the AlGaAs barrier layer. Little bulge was observed in the gate current noise of the HEMTs with large InAs mole fractions of 0.4 and 0.5. Generation of the traps with different time constant can explain this behavior.

key words: *low-frequency noise, HEMT, Arrhenius plot, DX center, Lorentz noise*

1. Introduction

AlGaAs/InGaAs pseudomorphic HEMTs fabricated on GaAs substrate [1], [2] have attracted much attention. This is due to the large two-dimensional electron gas (2DEG) density, resulting from a large conduction-band discontinuity (ΔE_C) between the channel and barrier layers, as well as to a large electron velocity expected in the InGaAs channel. From this standpoint, it is better to use a larger InAs mole fraction for the InGaAs channel layer. In order to satisfy this requirement, various kinds of buffer layer technologies such as a compositionally graded InGaAlAs buffer layer [3], an InGaAs buffer layer [4], an InAlAs buffer [5], and a step graded InAlAs buffer layer [6] have been proposed. We have proposed a pseudomorphic/metamorphic modulation-doped heterostructure employing a thick $In_{x/2}Ga_{1-x/2}As$ buffer layer [7]. A large transconductance of 500 mS/mm was obtained for a 1.7-µm gate HEMT at x = 0.4. The cutoff frequency was 13.3 GHz.

Even though the AlGaAs/InGaAs pseudomorphic HEMTs have shown impressive performance, there is some concern about the effects of the misfit dislocation such as low-frequency noise and frequency dispersion of the drain current. These phenomena limit the performance for application such as nonlinear circuits that have noise upconversion, and ultrawide-bandwidth circuits. Even though the low-frequency noise characteristics have been intensively studied [8]–[11], further study is necessary to fully understand the behavior of the noise.

In this paper, we discuss the low-frequency noise of InGaAs pseudomorphic/metamorphic HEMTs fabricated on GaAs substrate. The gate voltage dependence of the noise was measured to clarify the dominant noise source. The generation-recombination (G-R) noise was also studied in detail by measuring the temperature dependence of the noise.

2. Experimental

The schematic cross-section of the measured HEMTs is shown in Fig. 1. The key technology of the device is to grow a thick (~1 µm) $In_{x/2}Ga_{1-x/2}As$ buffer layer on a GaAs substrate, where the InAs mole fraction is a half of the channel layer. Thus, this layer acts as a substrate with an intermediate lattice constant for the pseudomorphic HEMT. This permits us to use an $In_xGa_{1-x}As$ channel with a large InAs mole fraction x. The InAs mole fractions x in the channel of the fabricated device were 0, 0.2, 0.4 and 0.5. The AlAs mole fraction was 0.27. Details of the device performance and its temperature dependence are reported in the previous reports [7], [12].

The voltage fluctuations in the device were measured using a spectrum analyzer. The frequency range was 1 Hz to 10 MHz. Figure 2 shows the drain-current relative noise spectral density S_I/I^2 at 10 Hz as a function of the effective gate voltage (V_{GS}-V_{th}). The InAs mole fraction of the channel is 0.2. The device was biased in the linear region with V_{DS} of 0.3 V. At low effective gate voltage of less than 0.3 V, S_I/I^2 is inversely proportional to the effective gate voltage. When the effective gate voltage is larger than 0.3 V, S_I/I^2 is proportional to the minus third of the effective gate voltage. The device with different InAs mole fraction showed similar gate voltage dependence. The formalism concerning the gate voltage dependence of the noise spectral density S_I/I^2 developed by

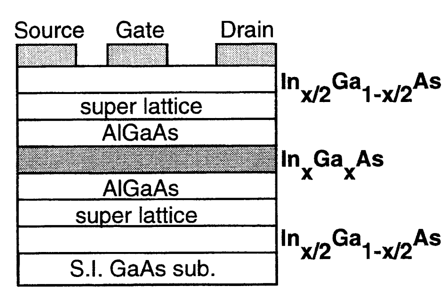

Fig. 1 Shematic cross-section of the AlGaAs/In_xGa_{1-x} As pseudomorphic HEMT.

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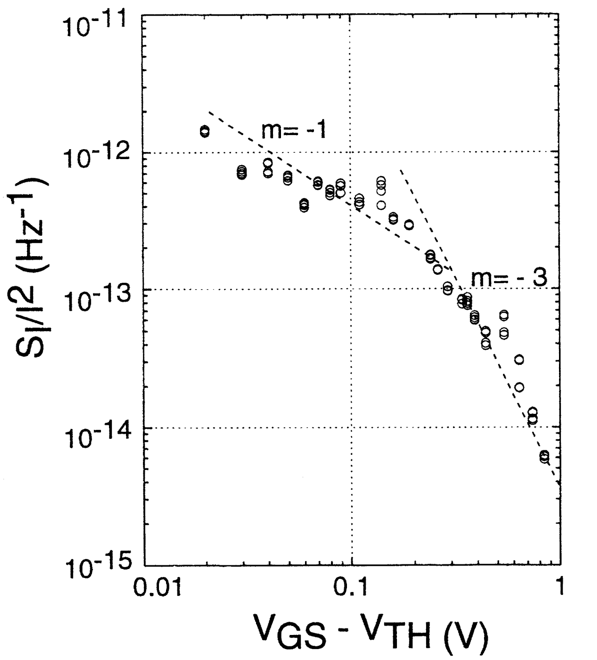

Fig. 2 Drain-current relative noise spectral density S_I/I^2 at 10 Hz as a function of the effective gate voltage. V_{DS}=0.3 V.

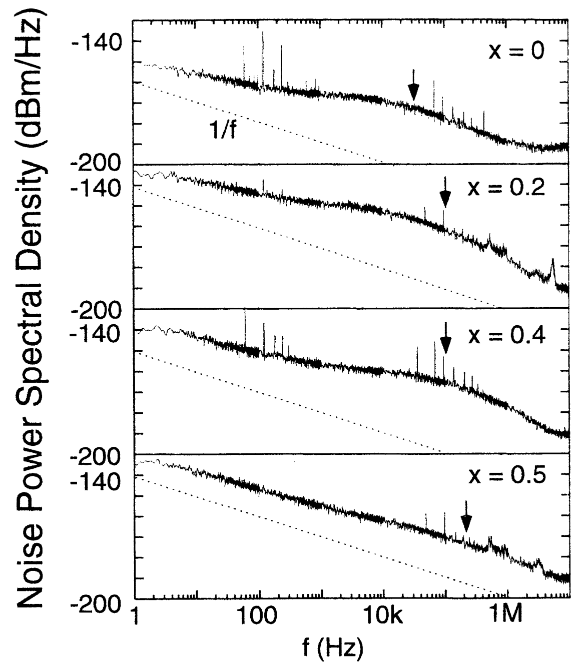

Fig. 3 Low-frequency noise spectra of the drain current at room temperature. V_{DS}=1.5 V, V_{GS}=0 V for x=0, 0.2, 0.4 and 0.5 V for x=0.5.

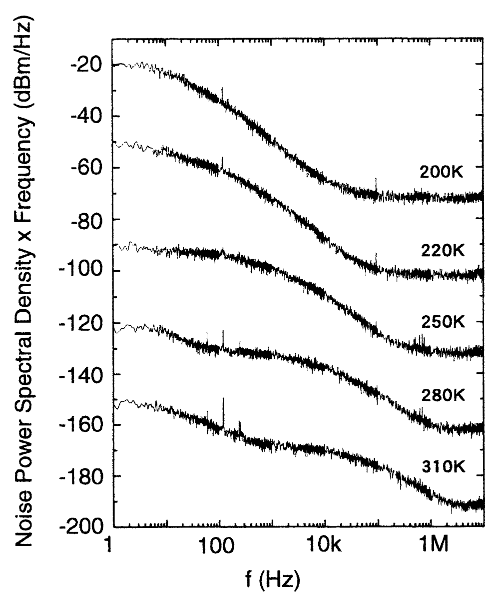

Fig. 4 Temperature dependence of the drain current noise spectra.

Peransin et al. [9] enables us to determine the origin of the low-frequency noise. It is summarized as follows.

(1) $S_I/I^2 \sim (V_{GS}-V_{th})^{-1}$: Resistance and the noise of the device are dominated by the channel.

(2) $S_I/I^2 \sim (V_{GS}-V_{th})^{-3}$: Resistance is dominated by the parasitic series resistance but the noise is dominated by the channel.

(3) $S_I/I^2 \sim (V_{GS}-V_{th})^{0}$: Resistance and the noise are dominated by the parasitic series resistance.

Based on this formalism, we can conclude that the low-frequency noise in the present device is dominated not by the series resistance but by the channel of the device.

Figure 3 shows the measured low-frequency noise spectra of the drain current. Here, the devices was operated under drain current saturation condition, since this was the normal mode of their operation for amplification purposes. The bulge which reflects Lorentz noise is superimposed on a background of 1/f noise at around several tens kHz for all devices with different InAs mole fraction as shown in the figure. It is interesting to note that the Lorentz noise was observed even in the HEMTs with no InAs in the channel. This suggests that the In is not responsible for the present Lorentz noise. The Lorentz noise reflects the existence of the G-R noise.

In order to study the origin of the noise bulge, the temperature dependence of the low-frequency noise spectra was studied. The temperature was changed between 200 and 310 K. The measured result for the device with x=0 at V_{DS} = 1.5 V and V_{GS} = 0 V is shown in Fig. 4. The corner frequency (ω_c = $1/\tau$) at which the Lorentz spectrum crosses the 1/f noise curve represents characteristic time constant of the G-R noise. As the temperature decreases, ω_c decreases and the plateau level increases as expected by the expression for the Lorentz noise; $S(\omega)=C\tau/(1+\omega^2\tau^2)$, here C is the proportional constant. The $\tau=1/\omega_c$ change affects much more the numerator rather than the denominator of the $S(\omega)$ expression.

The corner frequency ω_c can be evaluated more precisely by plotting the (noise power spectral density) × (frequency) products as a function of the frequency. This enhances the bulges, resulting in clear peaks as shown in Fig. 5. As the temperature decreases, the Lorentz spectra move to lower frequencies reflecting the longer time constant of the G-R noise. The activation energies E_a of the traps can be evaluated from

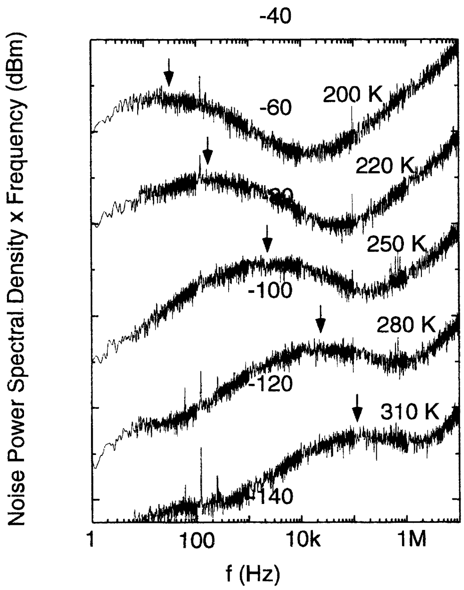

Fig. 5 (noise power spectral density) × (frequency) products as a function of the frequency.

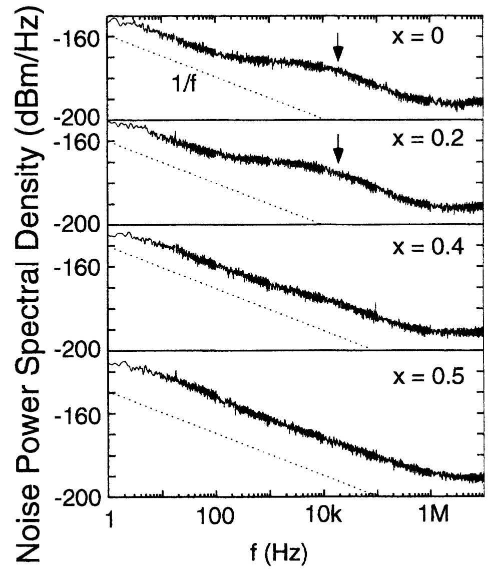

Fig. 7 Low frequency noise spectra of the gate current at room temperature. V_{DS}=1.5 V, V_{GS}=0 V for x=0, 0.2, 0.4 and 0.5 V for x=0.5.

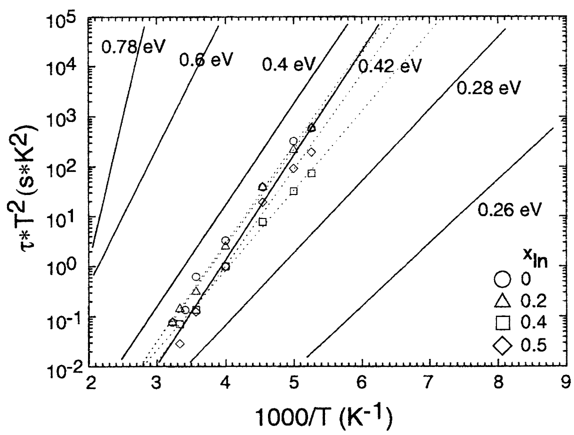

Fig. 6 Arrhenius plots of the time constant of the drain current noise. Solid lines are the deep levels of other reports.

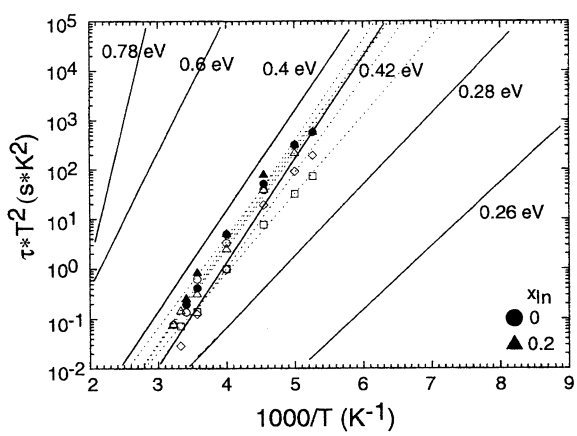

Fig. 8 Arrhenius plots of the time constant of the gate current noise. Solid symbols: gate current noise, open symbols: drain current noise.

Arrhenius plots according to the following equation:

$$1/\tau = \omega_c = \sigma T^2 \exp(-E_a/kT)$$

where T is the measurement temperature, σ is the capture cross-section and k is the Boltzmann constant.

The Arrhenius plots of the time constant obtained from such characteristics are shown in Fig. 6 by open symbols for the HEMTs with different InAs mole fractions. Solid lines in the figure show the deep levels of other reports [13], [14]. The activation energies of the present G-R noise were 0.39, 0.38, 0.32, and 0.37 for the devices with x=0, 0.2, 0.4, and 0.5, respectively. The activation energy obtained here is close to that of DX center, 0.42 eV. This suggests that the Lorentz noise obtained here is probably due to the DX center in the AlGaAs barrier layer.

Figure 7 shows the measured low-frequency noise spectra of the gate current. The bulge is observed for the devices with x=0 and 0.2 at around several tens kHz. The Arrhenius plots of the time constant of the gate current noise are shown in Fig. 8 by solid symbols together with the results of drain current noise (open symbols). Both data are plotted on the same area. The activation energies of the gate current noise were 0.38 and 0.39 eV for the HEMTs with x=0 and 0.2. These are almost the same as those of the drain current. This suggests that the origin of the gate current noise is also the DX center in the AlGaAs barrier layer. The reason of little bulge for the device with x=0.4 and 0.5 can be explained if we take into account the fact that many misfit dislocations would be generated in the channel because of the large lattice mismatch, resulting in the generation of the traps. If the distribution of the time constant of the traps is proportional to the inverse of the time constant, the noise spectrum changes from Lorenzian to 1/f dependence [15]. The misfit dislocation observed by TEM for the wafer with x=0.5 supports this

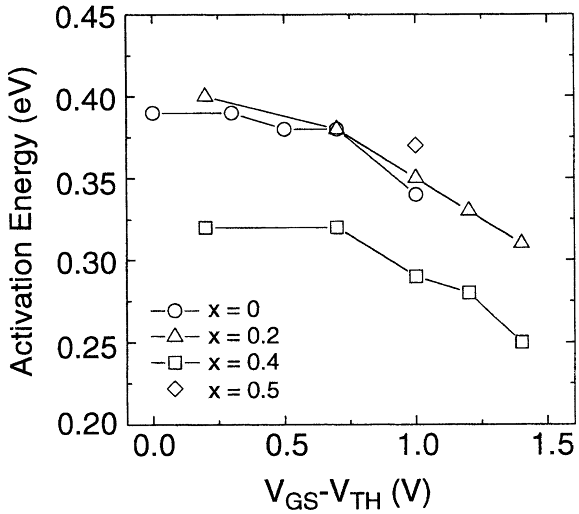

Fig. 9 Activation energy as a function of the effective gate voltage.

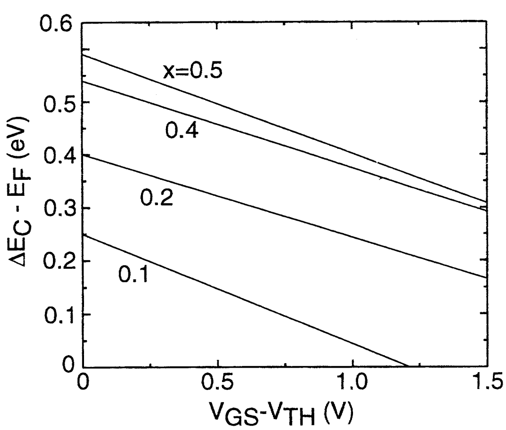

Fig. 10 Calculated barrier height for the real-space transfer as a function of the effective gate voltage.

explanation.

Figure 9 shows the dependence of the activation energy of the drain current noise on the effective gate voltage. The activation energy decreases with increasing the gate voltage. This means that the barrier height against the generation and recombination of the carriers is dependent on the gate voltage. The activation energy of the DX center is not dependent of the gate voltage. Then it is necessary to consider the contribution of other mechanism. One of the plausible origins is the real-space transfer of electrons over the hetero-barrier [11]. The real-space transfer of the electrons between the channel and the AlGaAs barrier layer will cause the fluctuation of electron density resulting in the G-R noise. In this case, the activation energy decreases by increasing the gate voltage because of the increase of the fermi energy of the 2D-electron gas at the AlGaAs/GaAs interface. The calculated barrier height for the real-space transfer (ΔE_c-E_f) is shown in Fig. 10 as a function of the effective gate voltage. The experimental results agree qualitatively with the calculated results. This supports the argumens that the real-space transfer contributes to the G-R noise.

3. Conclusion

We have studied the low-frequency noise of InGaAs pseudomorphic/metamorphic HEMTs fabricated on GaAs substrate. It was shown from the gate voltage dependence of the noise spectral density that the low-frequency noise is dominated not by the series resistance but by the channel of the device. Generation-recombination noise was observed in the low-frequency noise in the form of bulges superimposed on a background of 1/f noise at around several tens kHz at room temperature. The activation energy was evaluated from the temperature dependence to be 0.32–0.39 eV which is close to that of the DX center. This suggests that the origin of the G-R noise is the DX center in the AlGaAs barrier layer. Little bulge was observed in the gate current noise of the HEMTs with large InAs mole fractions of 0.4 and 0.5. This was explained by assuming the traps with different time constant that would be introduced in the channel.

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