Low-frequency noises in GaAs MESFET's currents associated with substrate conductivity and channel-substrate junction

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Low-frequency noises in GaAs MESFET are usually observed when investigating the drain current and substrate leakage current under sidegate bias conditions. Experimental results show that the magnitude of low-frequency noises is in a direct dependency upon the sidegate bias and the noises in drain current will disappear if sidegate bias increases more negatively beyond a certain voltage. A mechanism associated with the substrate conductivity and the channel-substrate junction modulated by sidegate bias is proposed to explain the fluctuation of low-frequency noises.

MESFET, low-frequency noise, substrate conductivity, channel-substrate junction

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MESFET is considered as one of the important devices for the applications of high power, high frequency and high efficiency microwave electric circuit [1,2]. However, as the demand for higher speeds and increased functionality in circuits, low-frequency noises (LFN) in currents, such as thermal noise, $1/f$ noise, generation-recombination noise, diffusion noise and shot noise, in various GaAs FET structures have been reported [3–10]. The main characteristics of these noises are: (1) LFN strongly depends upon the substrate materials. (2) The frequency of LFN is in the range of about 10^{-2} to 10^2 Hz. (3) LFN is dependent on the fabrication procedure and bias condition. (4) LFN is sensitive to illumination. Recently LFN has received more attention due to its effect on the performance of low-noise microwave integrated circuits (MMICs).

Although it is generally accepted that LFN results from the field-enhanced capture of electrons by deep traps, the exact mechanism is not fully understood. Miller and Bujatti attributed LFN directly to the oscillations in leakage currents in the semi-insulating (SI) GaAs substrate [5]. While Wager pointed out that LFN in channel current could not be

simply attributed to the oscillations in leakage current of the substrate, but related to the peculiarities of channel-substrate junction [9].

In this paper, LFN in MESFET's currents is investigated under sidegating conditions, and the mechanism is identified whereby the current fluctuation is directly related to the sidegate bias. Unlike Birbas's explanation in terms of an unreal negative capacitance of the depletion region in buffer-channel interface [11], we associate LFN with the substrate conductivity and channel-substrate junction modulated by sidegate bias. This study should be of value to elucidate the fundamental nature of noises modulation in GaAs ICs.

1 Experiments and results

The test pattern in this study is shown in Figure 1(a). The device structure and schematic used for electrical measurements are shown in Figure 1(b). FETs are fabricated on undoped liquid-encapsulated Czochralski (LEC) SI GaAs substrate by selective ion implantation. The test device comprises a $10\ \mu\text{m} \times 10\ \mu\text{m}$ sidegate (SG) and a FET with a

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Figure 1 The test pattern and device structure for investigating LFN. (a) The test pattern used in LFN investigation; (b) the device structure and schematic used for electrical measurements.

10 $\mu\text{m} \times 2 \mu\text{m}$ gate (G). The distance between SG and the FET is 20 μm . Silicon ions are implanted at the energy of 60 keV with a dose of $6 \times 10^{12} \text{ cm}^{-2}$ for n layer, and at 30 keV with a dose of $1.5 \times 10^{13} \text{ cm}^{-2}$ for n^+ region. Electrical isolation is achieved by Boron ions implantation at 80 keV with a dose of $8 \times 10^{12} \text{ cm}^{-2}$. Short annealing is carried out at 940°C with 10 s. The gate metals used are Ti/Pt/Au, and metals for Ohmic contacts are Au/Ge/Ni/Au. The fringe portions of all these contacts and probe pads are in contact with the substrate.

Measurements are made at room temperature with a HP4145B semiconductor parameter analyzer and a Karlsuss testing instrument. The “Integ time” of HP4145B is set to “short”, and the “delay time” is set to 1 s. In the experiments, the substrate is kept floating; the source of FET is grounded; the gate bias (V_{GS}) of FET varies from 0 V to –3 V, and the sidegate bias (V_{SG}) varies negatively from 0 V to –20 V with a step of 30 mV. To investigate LFN in the currents of MESFET, drain current (I_{DS}) and substrate leakage current (I_{SG}) are recorded.

In the experiments, $I_{\text{DS}}-V_{\text{SG}}$ exhibits a typical sidegating effect as V_{SG} increases negatively, as shown in Figure 2(a). Sidegating effect is that I_{DS} of MESFET will decrease abruptly when sidegate bias increases beyond a critical value [12,13]. And this critical value is defined as sidegating threshold voltage ($V_{\text{SG}}^{\text{th}}$). The sidegating threshold voltage in Figure 2(a) is about –3.8 V. From Figures 2(b)–(f), remarkable LFN can be observed in channel current with sidegate bias varying negatively. In disagreement with the previous work, interesting phenomena are found that: (1) The magnitude of LFN increases as V_{SG} increases negatively. (2) The oscillations of LFN get the greatest in degree while V_{SG} reaches $V_{\text{SG}}^{\text{th}}$. (3) LFN will disappear when V_{SG} increases more negatively beyond a certain voltage (V_{C}). In short, LFN in the channel current of MESFET has a direct dependency upon the sidegate bias conditions. (4) From Figures 2(b) and (f), we can see that the saturation current with $V_{\text{SG}} = -5 \text{ V}$ is less than that with $V_{\text{SG}} = 0 \text{ V}$.

In the experiments, $I_{\text{DS}}-V_{\text{GS}}$ is recorded at different sidegate bias, as shown in Figure 3. LFN can also be observed

in $I_{\text{DS}}-V_{\text{GS}}$. It can be founded that the noises will also disappear when V_{SG} increases beyond a certain voltage.

Since it is well known that the sidegating effect is strongly material dependent, some attempts are made to measure LFN in the substrate leakage current. In the experiments, I_{SG} is recorded as a function of V_{SG} which increases negatively from 0 V to –20 V. The experimental results are shown in Figure 4, in which I_{SG} exhibits an apparent LFN. Unfortunately, although remarkable LFN can be observed in leakage current, we can not find the same behavior as the LFN in channel current where the LFN will disappear if V_{SG} increases beyond a certain voltage.

2 Discussion

Based on the experimental results presented above, we propose that the substrate conductivity and channel-substrate junction which are modulated by the sidegating voltage take full responsibility for the LFN in currents of GaAs MESFET.

On the one hand, in the sidegating backward biased regime, the resistivity of SI substrate is a variable with different V_{SG} , illustrated as in Figure 5. In general, the resistance of SI substrate (R_{sub}) is typically of $10^7-10^9 \Omega \text{ cm}$. As V_{SG} increases negatively, electron emission manifolds gradually in the SI substrate. Thus, the resistivity of the substrate decreases more or less following a linear proportionality to V_{SG} , as illustrated in Region I. If V_{SG} becomes more negative than $V_{\text{SG}}^{\text{th}}$, the substrate will be taken in the charge of high electric field whose intensity is approximately 10 kV/cm. The free electrons under the high electric field will gain enough energy to excite the trapped electrons in deep traps exhibiting an avalanche multiplication effect. That is to say, impact ionization will take place. In this state, R_{sub} reduces dramatically with a super linear behavior, as illustrated in Region II. When V_{SG} reaches a certain voltage where the deep traps are almost fully ionized, R_{sub} will resume Ohmic characteristics, as illustrated in Region III.

On the other hand, as is well known, channel-substrate junction (C-S junction) plays a significant role in sidegating effect of GaAs MESFETs [9,12–17]. The illustration of the C-S junction can be referred to in Figure 1(b). The space-charge distribution of the C-S junction resembles a p-n junction with depletion region located in doped channel and formed by the charge of ionized donors. Expansion of the depletion region on the substrate side under external electric field is accompanied by electrons captured in deep traps, while contraction of the depletion region is accompanied by electrons emission from deep traps to conduction band.

The equivalent circuit of the test structure used in LFN investigation under sidegate bias conditions is shown in Figure 6. R_{S} is the surface leakage resistance. R_{CS} is the resistance of C-S junction. With sidegate bias, because R_{sub} is

Figure 2 LFN in channel current as sidegate bias increasing negatively. (a) Sidegating effect of GaAs MESFET; (b) LFN in channel current with $V_{SG} = 0$ V; (c) LFN in channel current with $V_{SG} = -0.8$ V; (d) LFN in channel current with $V_{SG} = -3$ V; (e) LFN in channel current with $V_{SG} = -3.8$ V; (f) LFN in channel current with $V_{SG} = -5$ V.

series connected with R_{CS} , V_{SG} partly drops across the substrate (the voltage is denoted as V_{sub}) and partly drops across the C-S junction (the voltage is denoted as V_{CS}). From the analysis shown above, R_{sub} varies with V_{SG} , consequently, the voltage drops across the C-S junction changes correspondingly. That is to say, V_{CS} is modulated by the change of R_{sub} .

The LFN can be analyzed with Khuchua's model of drain current versus V_{SG} [12],

$$\frac{\Delta I_{DS}}{I_{DS0}} = \frac{1}{\sqrt{1 + N_D / N_{traps}}} \times \frac{\sqrt{V_{CS}}}{\sqrt{V_b - V_{T0}} - \sqrt{V_b}} \times \left(\sqrt{1 + \frac{V_{sub} - V_{SG}}{V_{CS}}} - 1 \right), \quad (1)$$

where I_{DS0} and V_{T0} are the drain current and the FET threshold voltage at $V_{sub} = 0$ V, respectively, V_b is the Schottky built-in voltage, N_D is shallow donor density, N_{traps} is the concentration of vacant deep traps.

According to eq. (1), the irregular varieties of V_{CS} and V_{sub} give rise to ΔI_{DS} , thus the fluctuations of I_{DS} generate. In Region I of Figure 5, as V_{SG} increases negatively, R_{sub} decreases more or less following a linear proportionality to V_{SG} . The variety in R_{sub} will give cause for the increase of V_{CS} which exerts an influence on the depletion width of C-S junction, resulting in the aggravation of oscillations in the depletion width. These oscillations have direct relationship with the fluctuations in channel current and leakage current and they affect the magnitudes of LFN, as shown in

Figure 3 LFN in drain current versus gate bias with different sidegate bias.

Figure 4 LFN in substrate leakage current as sidegate bias increases negatively.

Figure 5 The behavior of substrate resistivity versus backward sidegate bias.

Figure 2(b)–(d) and Figure 4.

In region II, as the superlinear decrease of R_{sub} , V_{sub} decreases and V_{CS} increases dramatically. As a result, an expansion of C-S junction depletion on the channel side mag-

Figure 6 The equivalent circuit of the test structure used in LFN investigation with sidegate bias.

nifies [16]. Meanwhile, there is some hysteresis in the response of the depletion region expansion of C-S junction on the variation of external electric field caused by V_{SG} [17]. These two factors give rise to larger fluctuations of the depletion region thickness in C-S junction which modulate the effective width of FET channel strongly. In consequence, the fluctuations of LFN in channel current get a great magnitude, as shown in Figure 2(e).

In Region III, R_{sub} resumes Ohmic characteristics and gets stable and low resistance. In this case, the modulation on V_{CS} caused by R_{sub} can be negligible, so V_{SG} mainly drops across the C-S junction. As a result, LFN in current disappears, as shown in Figure 2(f) and Figure 3. Meanwhile, with V_{SG} becoming more negative, the expansion of C-S junction depletion on the channel side reduces the channel width greatly, the sidegating effect will take place, so saturation channel current declines, as shown in Figure 2(f).

In addition, as shown in Figure 4, although remarkable LFN can be observed in substrate leakage current and it has a direct relation with V_{SG} , it is not found that there is a certain voltage beyond which LFN disappears. A possible cause is that the substrate leakage current recorded in our experiments is only the current from the substrate to the sidegating electrode. In fact, the total leakage current should consist of currents from the FET active region, from the gate pad located on the SI substrate, and from the grounded substrate [5]. In the further research, we will make a thorough investigation on the LFN in leakage current and try to find its relationship with the LFN in drain current.

3 Conclusions

LFN in MESFET's currents is investigated under sidegate bias conditions. It is found that the fluctuation of LFN is directly related to the sidegate bias. In disagreement with the earlier work, an interesting phenomenon is observed that LFN will disappear when sidegate bias increases more negatively beyond a certain voltage. It is argued in this paper that LFN in the currents of MESFET associates with the substrate conductivity and channel-substrate junction which are modulated by sidegate bias.

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