Flicker Noise of AlGaN/GaN Metal-Oxide-Semiconductor Heterostructure Field-Effect Transistor with a Photo-CVD SiO2 Layer

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The effects of drain-source distance and applied voltage on low-frequency noise behavior of AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistors incorporated with a photochemical vapor deposited (photo-CVD) SiO2 gate oxide layer were investigated. According to our studies, the normalized noise power density is inversely proportional to \( I^{-1} \) \((=L_{d}^{-1}−L_{pad})\) when devices are biased in the linear region. However, the drain-source distance alone exerts little influence on low-frequency noise in the saturation and cutoff regions. Furthermore, the \( f^{1/2} \) noise characteristics and the \( f \) value were affected by the interface state distribution in the energy bandgap as the gate bias was varied. The normalized noise power density determined is independent of the drain-source voltage in the linear region, but it exhibits an enhancement in the saturation region in response to an increase in the drain-source voltage. However, the noise power density then becomes constant when devices are biased in the cutoff region.

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Gallium nitride (GaN) and its related compounds possess excellent physical and electrical properties, which include wide bandgap, high breakdown field, high saturated electron drift velocity, and good thermal stability. These properties make them particularly useful for applications in high-speed, high-power, and high-frequency electronic devices operating at elevated temperatures. In the past years, GaN-based transistors, such as metal-semiconductor field-effect-transistors (MESFETs), heterostructure FETs (HFETs), and high electron mobility transistors (HEMTs) have all been reported. However, the performance of these devices still remains inadequate. Because the surface of nitride-based epilayer is defective in general, it is difficult to achieve high-quality Schottky contacts. As a result, high gate leakage currents are often observed in devices such as MESFETs, HFETs, and HEMTs. Gate leakage currents to a large extent are smaller in magnitude for other devices such as metal-insulator-semiconductor FETs (MISFETs) and metal-insulator-semiconductor HFETs (MIS-HFETs). In the past, the fabrication of GaN-based MISFETs and MIS-HFETs using SiN, GGG, Ga2O3, Gd2O3, SiO2, MgO, Sc2O3, and stacked multilayer oxide as the insulating materials have all been demonstrated. 4,11

Previously, we have shown that photochemical vapor deposition (photo-CVD) with deuterium (D2) excitation source could potentially be used for growing high-quality SiO2 layers on top of various semiconductors. In particular, depositing gate oxide layers on III-nitride-based metal-oxide-semiconductor HFETs (MOS-HFETs) via photo-CVD have already been demonstrated. 12,20

It is well-known that low-frequency noise (LFN) is considered one of the most important figures of merit to assess the performance of microwave devices. Devices with a lower LFN level have already been proven suitable for microwave and communication applications. Previously, Rumyantsev et al. reported a study on the low-frequency noise of a nitride-based MOSFET incorporated with a SiO2 layer using plasma-enhanced chemical vapor deposition (PECVD). 21,23 In this study, nitride-based MOS-HFETs with a photo-CVD SiO2 oxide layer were fabricated. A detailed study on LFN of the fabricated devices biased at various conditions is reported.

Experimental

The structures of the AlGaN/GaN MOS-HFETs with a photo-CVD SiO2 oxide layer adopted in this study were all grown on c-face (0001) 2 in. sapphire (Al2O3) substrates by metalorganic chemical vapor deposition (MOCVD). The structures consist of a 30 nm thick low-temperature GaN nucleation layer, a 2 \( \mu \)m thick unintentionally doped GaN layer, a 5 \( \mu \)m thick unintentionally doped Al0.22Ga0.78N spacer layer, a 15 \( \mu \)m thick Si-doped Al0.22Ga0.78N carrier supplying layer \((n = 5 \times 10^{19} \text{ cm}^{-2})\), and a 4 \( \mu \)m thick unintentionally doped Al0.22Ga0.78N cap layer. From Hall measurements, room-temperature carrier mobility and sheet carrier concentration of the as-grown samples were determined as 800 \text{ cm}^{2} \text{V}^{-1} \text{s}^{-1} and 9.8 \times 10^{12} \text{ cm}^{-2}, respectively. Mesa etching was then performed using an inductively coupled plasma (ICP) etcher with Cl2/Ar as the etching gases for device isolation. During ICP etching, we kept the Cl2 flow rate, Ar flow rate, ICP power, rf power, and chamber pressure at 10 sccm, 25 sccm, 450 W, 150 W, and 3 mTorr, respectively. 21,23 Next, Ti/AI (10 nm/180 nm) was thermally evaporated to serve as the source and drain ohmic contact electrodes, followed by a 670°C furnace annealing in N2 ambient for 6 min. Afterward, a 32 nm thick gate oxide was then deposited on the samples by photo-CVD with a 150 W D2 lamp. During SiO2 deposition, we kept the process pressure, substrate temperature, and SiH4/O2 gas ratio at 0.9 Torr, 300°C, and 0.055, respectively. 21,23 Finally, the fabrication of AlGaN/GaN MOS-HFETs was completed after Ni (40 nm)/Au (80 nm) gate metal was deposited via standard photolithography and metal evaporation. 21,23 The drain-source distance of these devices varies from 5 to 20 \( \mu \)m and the gate metal dimension is 2 \( \times 100 \) \( \mu \)m.

The LFN of the fabricated devices was then measured by, respectively, biasing these devices in the linear region (i.e., \( V_{gs} = 0 \text{ V}, \ V_{ds} = 3 \text{ V} \)), saturation region (i.e., \( V_{gs} = 0 \text{ V}, \ V_{ds} = 12 \text{ V} \)), and cutoff region (i.e., \( V_{gs} = −8 \text{ V} \)) over the frequency range of 1 Hz to 10 kHz. During the LFN measurements, the drain current was amplified by a low-noise amplifier. The bias conductances were supplied and controlled by a BTA Noise Pro system. The noise power spectra were then analyzed by an HP35670A dynamic signal analyzer and a BTA 9812 noise analyzer. A metal resistor was employed to load the drain and also to define the drain current. We also placed an additional capacitance in between the gate and source in order to isolate the device away from the unwanted noise. All measurements were performed at room temperature.

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Results and Discussion

The effect of drain-source distance on LFN.— As shown in Fig. 1, the total LFN of our MOS-HFETs between source and drain could be given by (the contribution of gate leakage current and contact resistance to noise is negligible for our devices)

\[ S_{\text{total}} = S_{R_{\text{ch}}} + S_{R_{\text{g}}} \]

where \( S_{R_{\text{ch}}} \) is the total, \( S_{R_{\text{ch}}} \) is the noise originated from the region underneath the gate, and \( S_{R_{\text{g}}} \) is the noise originated from the ungated region. The total resistance between source and drain is given by

\[ R_{\text{total}} = R_{\text{ch}}(V_{gs}) + R_{S} \]

where \( R_{\text{ch}} \) is the channel resistance of the region underneath the gate (i.e. a function of \( V_{gs} \)), \( R_{S} \) is the series resistance (i.e., ungated region, which is independent of bias voltage), \( L_{\text{ch}} \) is drain-source distance, \( L_{\text{gate}} \) is the length of the gate (2 \( \mu \)m), \( W \) is the width of the channel (100 \( \mu \)m), \( q \) is the charge of an electron, \( \mu \) is the two-dimensional electron gas (2DEG) mobility, and \( n_{\text{sh}} \) is the sheet carrier concentration. The channel and series resistances in each mode of operation are summarized in Table I. In Table I, the channel resistance can be determined by the total channel resistance and series resistance, i.e., \( R_{\text{total}} \) and \( R_{S} \) are calculated from the dynamic resistance of the \( f-V \) curve and Eq. 2, respectively. Then, the LFN power spectra of the device with different drain-source distance (from 5 to 20 \( \mu \)m, step 5 \( \mu \)m) were all measured by biasing in the linear region (\( V_{gs} = 0 \) V, \( V_{ds} = 3 \) V), as shown in Fig. 2a. The normalized LFN spectra could all be reasonably fitted by the 1/f law up to 10 kHz. Then, the normalized noise power density with different drain-source distances at 1, 10, 100, and 1 kHz was extracted. As shown in Fig. 2b, the normalized noise power density of the devices is inversely proportional to \( L' = (L_{ch} - L_{gate}) \), where \( L_{ch} \) is gate length. As shown in Table I, the LFN of our MOS-HFETs is dominated by the parasitic series resistance, \( R_{S} \), (i.e., ungated region) when the device is biased in the linear region. Thus

\[ R_{\text{total}} = R_{ch} + R_{S} = \frac{(L_{ch} - L_{gate})}{q\mu n_{sh}} \]

\[ n_{sh} = (L_{ch} - L_{gate})/qR_{S} \times (L_{ch} - L_{gate}) \]

\[ S_{R_{\text{total}}} = S_{R_{ch}} + S_{R_{g}} = S_{R_{S}} \]

Table I. The channel and series resistances in each mode of operation for our fabricated MOS-HFETs from experiments.

<table>
<thead>
<tr>
<th>ALGaN/GaN MOS-HFETs with Photo-CVD SiO2</th>
<th>Linear region (( V_{gs} = 3 ) V, ( V_{ds} = 0 ) V)</th>
<th>Saturation region (( V_{gs} = 12 ) V, ( V_{ds} = 0 ) V)</th>
<th>Cutoff region (( V_{gs} = -8 ) V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_{S}</td>
<td>R_{ch}</td>
<td>R_{ch}</td>
<td>R_{ch}</td>
</tr>
<tr>
<td>24 ( \Omega )</td>
<td>146 ( \Omega )</td>
<td>1124 ( \Omega )</td>
<td>146 ( \Omega )</td>
</tr>
</tbody>
</table>

Figure 2. (a) Normalized noise spectra of the fabricated MOS-HFETs with different drain-source distance. Here, the devices were all measured by biasing in linear region (i.e., \( V_{gs} = 0 \) V, \( V_{ds} = 3 \) V), (b) Normalized noise power density as functions of drain-source distance at different frequency.

where \( n_{sh} \) is the sheet carrier concentration, \( \alpha \) is the Hooge’s coefficient, and \( f \) is the frequency. All of these spectra can be fitted by the 1/f’ law with an increase of gate bias voltage. We attribute this phenomenon to the spatial distribution of the 1/f’ noise with exponent \( \Gamma \) equal to unity. Further, theoretical results also agree very well with our experimental results. Furthermore, the Hooge’s coefficient \( \alpha \) was estimated to be around 10^{-3}. Such a value is similar to those reported by others.26,27

Figure 3a shows the normalized noise power spectrum of an MOS-HFET with different gate bias voltages in the saturation region (i.e., \( V_{gs} \) from 4 to –8 V, step –2 V, and \( V_{ds} = 12 \) V). It was found that the LFN was dominated by the 1/f’ noise at \( V_{gs} = -8 \) V, but showed degenerated 1/f noise (i.e., the value of \( \Gamma \) increases to 2) with an increase of the gate bias voltage. We attribute this phenomenon to the spatial distribution of the interfacial trap states within the photo-CVD SiO2 oxide layer, as shown in Fig. 4.28-31 Figure 4a shows the interfacial trap states for the 1/f’ noise with exponent \( \Gamma \) equal to unity being uniformly distributed within \( V_{gs} < 0 \) V. Thus, the 1/f law is applicable only for the uniform distribution of interfacial trap states. Interfacial trap states for the 1/f’ noise with exponent \( \Gamma \) not equal to 1 are nonuniformly distributed instead, which renders a significant deviation from the 1/f law with an increase of gate bias voltage, as shown in Fig. 4b and c.26-29 Therefore, the value of \( \Gamma \) and the 1/f’ noise characteristics as a function of \( V_{gs} \) are affected by the interface state distribution in the energy bandgap. Furthermore, Fig. 3b shows the normalized noise power spectra of MOS-HFETs with
different drain-source distances. These spectra were all measured by biasing the devices in saturation region (i.e., $V_{gs} = 0$ V, $V_{ds} = 12$ V). The measured LFN in the saturation region is practically independent of the drain-source distance, which is understandable given the fact that LFN of our MOS-HFETs in the saturation region is dominated instead by the channel resistance underneath the gate region, as shown in Table I. Therefore, the effect of drain-source distance on the LFN becomes negligibly small in the saturation region.

In addition, the LFN spectra of the MOS-HFETs with different drain-source distances were also measured by biasing these devices in the cutoff region (not shown). It was found that LFN spectra of the fabricated MOS-HFETs could also be fitted reasonably well by the 1/f law up to 10 kHz. In the cutoff region, the channel resistance underneath the gate region is substantially larger than the parasitic series resistance (ungated region) (i.e., $R_{ch} \gg R_s$), as shown in Table I. Thus, the LFN of our MOS-HFETs is also dominated by the channel resistance, which renders the effect of drain-source distance on LFN in the cutoff region insignificant.

The effect of drain-source voltages on LFN.— Figure 5 depicts the measured noise density of an MOS-HFET as function of $V_{ds}$ in different biasing regions. During these measurements, a gate bias of $V_{gs} = 0$ V was applied. As shown in Fig. 5, the normalized noise power density remained at practically the same level in the linear region. However, in the saturation region the normalized noise power density was raised instead in response to an increase in the drain-source voltage. As graphically shown in Fig. 6a, when a device is biased in the linear region, the entire channel becomes conductive and the electrical field distribution in each $\Delta x$ remains approximately identical. Thus, the invariant carrier velocity in the conductive channel due to uniform electrical field would result in a lesser current fluctuation and smaller noise power density. When the device is biased in the saturation region, the channel becomes a triangular conductive region, as shown in Fig. 6b. Consequently, different electric fields in $\Delta x_1$ and $\Delta x_2$ result in a nonuniform carrier velocity or current in the channel. Thus, a larger current fluctuation contributes to a higher noise power density. In addition, the variation of the electric field in Fig. 6c is larger than that in Fig. 6b, and this in turn leads to a more severe current fluctuation. Therefore, noise power density increases as the drain-source voltage increases.
Figure 6. (Color online) The conductive channel distribution of the devices biased in (a) linear region, (b) saturation region, (c) saturation region with larger $V_{dd}$.

Figure 7 presents normalized noise density as function of $V_{ds}$ for a MOS-HFET biasing in the cutoff region. During these measurements, a gate bias of $V_{gs} = -8$ V was applied. The noise power density of the devices changed only slightly, which was believed due to a very large channel resistance when biasing the device in the cutoff region. Thus, we conclude that the LFN of MOS-HFETs is dominated by the channel resistance, as shown in Table I. As a result, the effect of drain-source voltage on LFN again becomes small.

Conclusion

The LFN of AlGaN/GaN MOS-HFETs with a photo-CVD SiO$_2$ gate oxide layer and their dependence on drain-source distance and voltage were investigated. Our results show that the normalized noise power density is inversely proportional to $L/L_{ch}$ when the device is biased in the linear region. However, the drain-source distance demonstrates no far-reaching effect on the LFN behavior of MOS-HFETs in the saturation and cutoff region. Furthermore, the $1/f$ noise characteristics and the $V$ value are affected by the interface state distribution in the energy bandgap as the gate bias is varied. The normalized noise power density determined is independent of the drain-source voltage when the device is biased in the linear region. However, in the saturation region the normalized noise power density increases accordingly as a result of an increase in the drain-source voltage. Finally, the drain-source voltage exerts no effect on the noise power density of devices, as the power remains invariant in the cutoff region.

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