

Low-frequency Noise Measurements of AlGaIn/GaN Metal-oxide-semiconductor Heterostructure Field-effect Transistors with HfAlO Gate Dielectric

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Abstract— We report on the low-frequency phase-noise measurements of AlGaIn/GaN metal-oxide-semiconductor heterostructure field-effect transistors (MOS-HFETs) employing HfAlO as the gate dielectric. Some devices tested exhibited noise spectra deviating from the well-known $1/f$ spectrum. These devices showed broad peaks in the noise-spectral-density vs. frequency plots, which shifted toward higher frequencies at elevated temperatures. The temperature dependence of the frequency position of this peak allowed us to determine the energy level of these excess traps as 0.22 ± 0.06 eV below the conduction band for the bias conditions employed.

Index Terms— Gate dielectric, generation-recombination, MOSHFET, noise measurement

I. INTRODUCTION

The use of gate insulators in GaN-based heterostructure field-effect transistors (HFETs) has been gaining attention lately for high-power and high-frequency applications.¹ The driving force behind this is the potential of reduction in gate leakage-current and the suppression of drain-current-collapse, both of which are desired in order to achieve the highest performance from an HFET.^{2,3} However, the oxide layer is not a panacea in that the performance and the reliability of a power device might suffer from the interface and bulk traps associated with the thin oxide layer.^{4,5,6} Analysis of these traps can be made easier by bringing to bear powerful tools in addition to the I-V and C-V measurement techniques. Thus, it is beneficial to implement more sensitive measurement and analysis techniques to monitor and characterize the charge traps of the gate dielectrics.

Low-frequency noise (LFN), particularly the generation-recombination (G-R) contribution, is very useful for analyzing semiconductor quality as well as that of the oxide and oxide semiconductor interface owing to the fluctuations in the channel current being affected by the trapping and detrapping of electrons.^{7,8,9,10} Therefore, the monitoring of the LFN could be utilized as a diagnostic tool to not only characterize but also eventually deduce the failure modes of the power

HFETs. In this letter, we show that LFN, measured with the integrated residual phase-noise setup is able to detect excess noise contribution due to the presence of the oxide as well as determining the energy level of a dominant (G-R)-like defect. The energy level of traps in HfAlO oxide layer under the gate of AlGaIn/GaN MOS-HFETs extracted from temperature-dependent measurements support the aforementioned contention in regard to the Shockley-Read-Hall (SRH) G-R theory.¹¹

II. DEVICE GROWTH AND FABRICATION

The MOS-HFET structure was grown on sapphire by metalorganic chemical vapor deposition (MOCVD). A 2.5- μm -thick undoped GaN buffer was deposited following a 250-nm-thick AlN initiation layer. Next, a 20-nm-thick AlGaIn barrier layer was grown with 25% Al mole fraction. The Hall-effect measurements yielded a sheet carrier density $n_s \approx 1.6 \times 10^{13} \text{ cm}^{-2}$ and the electron mobility $\mu_e \approx 1200 \text{ cm}^2/\text{Vs}$ at room temperature. The source and drain contacts were formed using a standard lift-off technique and a Ti/Al/Ni/Au (30/100/40/50 nm-thick) alloyed stack. Mesa isolation was performed in a SAMCO inductively coupled plasma (ICP) system using a Cl-based chemistry. A 7-nm-thick HfAlO layer was then deposited with atomic layer deposition (ALD). After opening windows to the source and drain pads via ICP etching for electrical access, the gate electrodes were deposited using standard lift-off procedure with Pt/Au (30/50 nm-thick) electrodes. The typical I_{DS} vs. V_{DS} family of curves for the fabricated MOS-HFETs are plotted in the inset of Fig. 1, where the pinch-off voltage is -5.2 V. The devices exhibited $9.7 \times 10^{-6} \text{ A/mm}$ gate-leakage current at a gate bias of -8 V. This gate leakage is one to two orders of magnitude less than the control devices without the gate dielectric. The I_{D} vs. V_{DS} plots of the MOSHFETs measured showed no significant difference among themselves.

III. MEASUREMENT RESULTS AND DISCUSSIONS

In order to monitor the noise in a larger span of offset frequencies we carried out the temperature-dependent phase-noise measurements using the Agilent E5500 test-set with a built-in phase detector (mixer). The single-sided-spur calibration technique was used to achieve the maximum sensitivity. We applied a 4 GHz carrier signal and monitored the single-sideband low-frequency response within a 100 MHz offset frequency. After an optimization process, the HFET

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gate and drain bias values were held fixed for all measurements at $V_{GS} = 0$ V, and $V_{DS} = 6.3$ V.

All the HfAlO-gated MOS-HFET devices tested were selected randomly within an area of approximately 1cm^2 on the same wafer. The measurements consistently manifested two types of behavior according to the noise-spectral-density (NSD) results: The first set of devices showed simple $1/f^\gamma$ dependence in the NSD vs. frequency [Fig 1]. The power constant γ was approximately equal to 1.2 at room temperature. The second type of devices exhibited a broad partition-noise peak, which could be attributed to the G-R noise arising from a certain type of trap level in the oxide bulk or interface [Fig2]. This shows the noise technique we used is sensitive to the trap-originated variations in the channel-noise spectra of the devices, which are grown and fabricated under seemingly identical conditions. The NSD monitored from the control devices did not show excess-noise with a definite time-constant, whereas about 40% of the MOS-HFETs exhibited the G-R broad peaks with varying intensities. This suggests that the distribution of the traps in the gate dielectric is not uniform most probably due to local variations in the surface preparation conditions prior to oxide deposition. Further investigations to clarify the origin of this behavior are underway.

The G-R noise in an HFET originates from traps that randomly capture and emit electrons, thereby causing fluctuations in the number of electrons which carry current in the channel. The NSD of the fluctuations in the number of carriers is given by

$$\frac{S_{\Delta n}}{\Delta n^2} = \frac{S_{\Delta n}}{N^2} = \frac{N_T}{N^2} \frac{\tau}{1 + (2\pi f \tau)^2}, \quad (1)$$

where τ is the time constant associated with the abovementioned transitions, N_T is the trap concentration, and N is the number of the electrons.¹²

Fig. 1 shows the representative data from the group of devices which exhibit $1/f^\gamma$ -type noise, where γ changes from 1.17 to 1.35 within the temperature range of 300K-450K. The excess noise over $1/f$ noise can be attributed to the G-R transitions explained by the number fluctuation theory.¹³ In general, the time constant and the relative energy levels of the traps differ. This leads to the frequency dispersion of the G-R noise originated from the traps residing in the HFET structure. Depending on the distribution of the trap time constants, the additional NSD at elevated temperatures may represent the form of $1/f^\gamma$ spectrum, where γ varies within a certain range as obtained from the data in Fig. 1. The excess noise-power is found to be 8.5 dB and 4.8 dB at frequencies 1 Hz and 1 kHz, respectively. These values are extracted from the difference of the two curves at 300 K and 450 K. However, another qualitative approach to explain the higher noise levels at elevated temperatures is the effect of mobility fluctuations. The mobility fluctuations due to phonon scattering and Coulomb scattering depend on the temperature strongly. Mobility decreases with increasing temperature due to the phonon-scattering caused by increased lattice vibrations, whereas the Coulomb scattering decreases, favoring the

mobility, because of the shorter interaction-time of the carriers with the charged impurities. The phonon-scattering effect is dominant among these processes yielding a lower carrier-mobility and a higher channel-current scattering.

The second group of devices showed that the employed noise technique enables us to detect the trap characteristics. As seen in Fig. 2, the data exhibit a G-R excess-noise, which indicates the presence of traps with a higher density and having a fixed time-constant. Since we did not observe this behavior in the layers without a gate dielectric, we surmise that this excess noise is due to the traps originating from the 7-nm-thick bulk HfAlO oxide or the oxide-AlGaN interface.

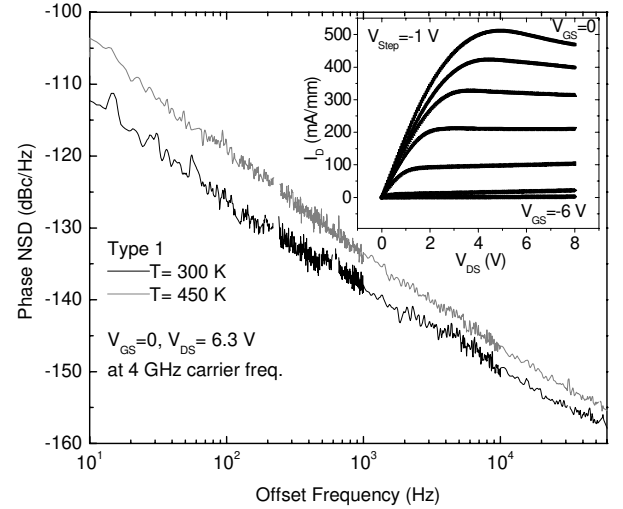


Fig. 1. Phase-modulation noise-spectral-density (PM-NSD) of an MOS-HFET. There is no discernible definite time-constant GR noise monitored. (Inset) The typical MOS-HFET I_D vs. V_{DS} family of curves with a $1\text{ }\mu\text{m}$ gate-length.

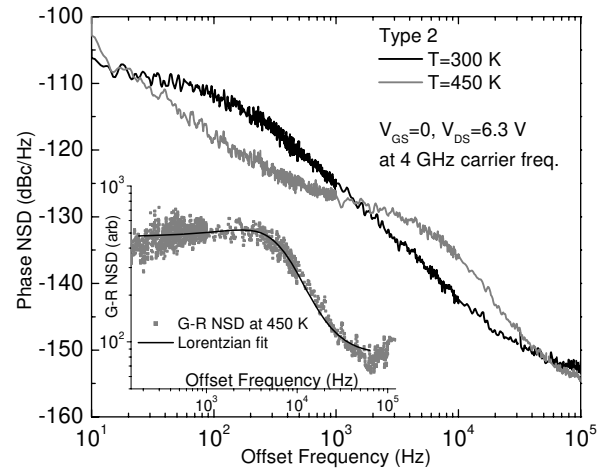


Fig. 2. PM-NSD of a MOS-HFET with G-R noise. (Inset) Lorentzian fit to the peak at 450 K after the subtraction of $1/f^\gamma$ background to obtain the lifetime of the traps.

Trapping and detrapping are processes that have strong lattice-temperature dependence.¹⁴ Thus, a careful analysis of the position of the broad G-R peaks in Fig. 2 with respect to temperature would allow us to extract the energy level of the traps within the forbidden gap. In order to achieve this, we

acquired the data from room temperature up to 450 K, and noted the shift of the peaks towards higher frequencies with increasing temperature. We fit the peaks to a Lorentzian function according to Eq. 1 following the subtraction of the $1/f$ background from the G-R spectra. This allows us to obtain the time constant for a certain temperature. The inset of Fig. 2 shows a sample Lorentzian fit for the data at 450 K. We found that the time constants fall in the range of 80 μ s-1ms within 300-450 K. These values are in agreement with predicted ones in Ref. [6].

The energy level of the traps can be found from

$$\tau_T = \tau_0 \exp\left(\frac{E_T}{kT}\right) \quad (2)$$

where τ_T is the trap time constant, E_T is the trap energy level below the conduction band, k is the Boltzmann constant. From the definition of Shockley-Read density, $\tau_0 = (\nu_n \sigma_T N_c)^{-1}$, where $\nu_n \propto T^{1/2}$ is the average drift velocity of the electrons, σ_T is the capture cross section of the traps, and $N_c \propto T^{3/2}$ is the density of states in the conduction band.^{6,10} In the inset of Fig. 3, we show the Arrhenius plot of the acquired trap-lifetimes at corresponding temperature values. From this analysis, the average trap energy level is extracted as 0.22 ± 0.06 eV. This value is smaller than that reported in Ref [4] for thin HfAlO films as measured by I-V and C-V. This discrepancy might be explained due to barrier lowering by the electric field (Frenkel-Poole effect) arising from the applied bias between the source-drain terminals.

Fig. 3 shows the effect of source-drain bias on the excess G-R noise. The arrow indicates that the peak shifted toward higher frequencies in the spectrum. The time constant of the traps decreased from 4.6 ms to 0.27 ms as we increased the V_{DS} from 10 V to 18 V. This affirms the abovementioned potential barrier lowering of the traps due to high electric fields. On the other hand, the NSD of the MOSHFETs exhibited no dependence on the gate bias, but the NSD monitored from the control FETs strongly depends on the gate bias over the frequency range of 1Hz-100 kHz. This feature implies that LFN of MOSHFETs is due to the number fluctuation and the noise is caused by the slow states.¹⁵

IV. CONCLUSION

Phase-modulated LFN measurements were used to monitor and analyze the G-R activity in the gate dielectric of HfAlO gated AlGaIn/GaN MOS-HFETs. In one group of devices, the noise level increased with increasing temperature due to the activation of traps with the lifetimes distributed over a large frequency range. We should note that the high electron-phonon scattering may contribute to this excess noise at the elevated temperatures. The second group of devices showed a deviation from $1/f$ spectra with broad G-R peaks. The trap energy level was calculated from these peaks as 0.22 ± 0.06 eV below the conduction band by Arrhenius analysis. The results show that the LFN is a very sensitive and useful diagnostic tool to characterize the AlGaIn/GaN MOS-HFETs, which would also be applicable to HFETs.

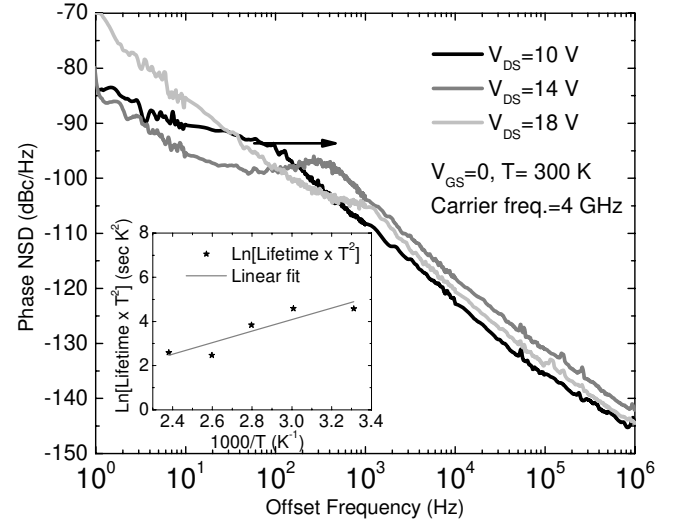


Fig. 3. NSD vs. frequency plot showing V_{DS} dependence of a MOSHFET. (Inset) Arrhenius plot of the acquired trap lifetimes for $V_{DS}=6.3$ V. The solid line is the linear fit, from which the trap energy was extracted.

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