Low-frequency noise and mobility fluctuations in AlGaN/GaN heterostructure field-effect transistors

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The $1/f$ low-frequency noise characteristics of AlGaN/GaN heterostructure field-effect transistors, grown on sapphire and SiC substrates by molecular beam epitaxy and organometallic vapor phase epitaxy, are reported. The Hooge parameter is deduced taking into account the effect of the contact noise and the noise originating in the ungated regions. A strong dependence between the Hooge parameter and the sheet carrier density is obtained, and it is explained using a model in which mobility fluctuations are produced by dislocations. A Hooge parameter as low as $\alpha_{\mathrm{CH}} \approx 8 \times 10^{-5}$ is determined for devices grown on SiC substrates. © *2000 American Institute of Physics.* [S0003-6951(00)02623-1]

Heterostructure field-effect transistors (HFETs) based on AlGaN/GaN are being studied due to their promising characteristics for power microwave circuits. Their superior performance in high power and high temperature applications has been recently demonstrated.[1] However, very limited information has been reported about the noise mechanisms in these devices.[2–5] It is well known that the low frequency noise, mainly $1/f$ noise, is upconverted to high frequency, limiting the performance of these transistors in the microwave range. A deep knowledge of the origin of the low frequency noise in HFETs is very important in low noise electronics for communications. We have previously reported a noise study in a limited set of AlGaN/GaN devices grown on sapphire substrates.[4] In this letter we have extended that study, and we report on low-frequency noise in AlGaN/GaN HFETs grown by different techniques on both sapphire and SiC substrates. The origin of the noise sources in those GaN-based devices has been investigated. It has been tentatively related to mobility fluctuations, due to fluctuations in the scattering rate of carriers with charged dislocations.

A significant set of HFET devices and ungated structures is studied. The AlGaN/GaN hererostructures were grown either on c-plane sapphire substrates (OM1, OM2, and OM3 samples), or on SiC substrates (OM4 samples), by organometallic vapor phase epitaxy.[6] AlGaN/GaN devices grown on sapphire substrate by molecular beam epitaxy (MBE) (MB1 sample) have also been included in this study.[7] In all heterostructure samples the Al content in the barrier is close to 30%, and the barrier thickness varies between 150 and 280 Å.

A complete direct current characterization has been performed in HFET devices and test structures. Hall mobilities and sheet carrier concentrations (n_s) in ungated structures were extracted from Hall measurements. The contact resistivity (ρ_c) and the sheet resistivity (ρ_s) were determined using a transmission line method (TLM) analysis. Capacitance–voltage measurements were carried out to determine the sheet carrier density (n_{CH}) under the gate and its dependence on the gate voltage (V_{GS}). The total drift mobility (μ_T) versus the sheet carrier density in the channel has been determined using ρ_c and ρ_s from the TLM results, and the measurements of the drain-source resistance (R_{DS}) at low drain bias (50 mV) as a function of V_{GS}. At low values of n_{CH}, a power-law dependence between the drift mobility and n_{CH}, $\mu_T \propto (n_{\mathrm{CH}})^k$, was found in all samples. The k exponent varies between 1.1 and 2 depending on the sample. The increase of the mobility with increasing n_{CH} is attributed to an enhanced carrier screening of the dominant scattering mechanisms.[8] At high values of n_{CH} (where V_{GS} is close to 0), a saturation trend in the mobility is observed in most of the samples, and it is attributed to lattice and/or roughness scattering.

On-wafer low-frequency noise measurements were performed at different gate-source voltages in the common source configuration ($V_{\mathrm{DS}} = 100\,\mathrm{mV}$). The noise spectra were obtained with a SR760 spectrum analyzer between 10 Hz and 100 KHz at 300 K. For each sample, the noise measurements were carried out in several HFET devices with different gate lengths and widths. The resulting drain voltage noise spectra were of $1/f^{\gamma}$ type, with the γ exponent varying between 0.8 and 1.3, depending on V_{GS}. Figure 1 shows the relative noise power density of sample OM3 at different V_{GS}. The drain voltage noise power density (S_{VDS}) depends quadratically on the applied drain-source voltage (V_{DS}), confirming that its physical origin is due to resistivity fluctuations. The contributions to the R_{DS} resistance fluctuations of the ohmic contacts (S_{RC}), ungated region (S_{RS}), and of the region under the gate (S_{RCH}), must be taken into account to analyze the drain-source voltage fluctuations. Assuming uncorrelated noise contributions, one can write

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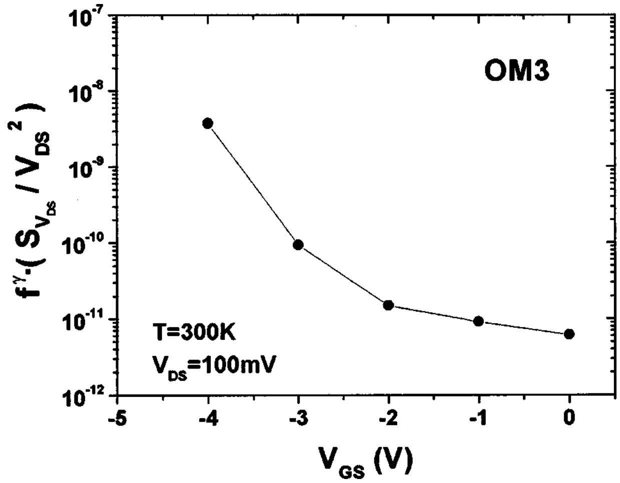

FIG. 1. Normalized noise power density (S_{VDS}/V_{DS}^2) vs the gate voltage for sample OM3, measured in the linear region of transistor operation ($V_{DS}=100$ mV).

$$\frac{S_{V_{DS}}}{V_{DS}^2}=\frac{S_{R_{DS}}}{R_{DS}^2}=\frac{S_{R_{CH}}+2S_{R_c}+S_{R_s}}{(R_{CH}+2R_c+R_s)^2}, \tag{1}$$

where Hooge's equation for S_{RC}, S_{RS}, and S_{RCH} can be expressed as[9]

$$\frac{S_{R_{CH}}}{R_{CH}^2}=\frac{\alpha_{CH}}{f^{\gamma}N_{CH}}, \quad \frac{S_{R_c}}{R_C^2}=\frac{\alpha_C}{f^{\gamma}N_C}, \quad \frac{S_{R_s}}{R_S^2}=\frac{\alpha_S}{f^{\gamma}N_S}, \tag{2}$$

with N_{CH}, N_C, and N_S being the number of electrons contributing to the current under the gate, in the ohmic contacts, and in the ungated areas, respectively. Also, α_{CH}, α_C, and α_S are the Hooge parameters associated with each noise region. Of these noise sources, only the noise produced at the gated region is a function of the gate voltage, due to the dependence of n_{CH} on V_{GS}. Moreover, it was previously reported that a dependence of α_{CH} on V_{GS} exists.[4] In this work, V_{GS} has been varied to distinguish between noise coming from the ohmic, ungated, and gated regions. The results of our analysis shows that in the $-2\text{ V}<V_{GS}<0\text{ V}$ region, the total noise power density is dominated by the ohmic contacts. In spite of the low contact resistivity (0.4–1 Ω mm), the noise contribution of the ohmic contacts is very important. In GaN material the ohmic contacts show a very rough surface with island-like morphology, pointing to the possibility of current constrictions that enhance the contact noise. Our results show that by improving contact technology, the total noise power density can be reduced by one order of magnitude (at $V_{GS}=0$ V).

From Eqs. (1) and (2), the noise contribution of the intrinsic device (gated and ungated regions) can be determined by subtracting the contact noise from the total noise. In Fig. 2, the Hooge parameter of noise sources in the channel (α_{CH}) of different samples is compared as a function of the number of carriers. Sample MB1 (on sapphire) shows a Hooge parameter as low as 2×10^{-4} at $V_{GS}=0$ V ($n_{CH}\approx1.05\times10^{13}$ cm^{-2}); and sample MOVPE4 (on SiC) shows an even lower Hooge parameter of $\alpha_{CH}\approx8\times10^{-5}$, at $V_{GS}=0$ V ($n_{CH}\approx1.39\times10^{13}$ cm^{-2}). These values are comparable to those reported in AlGaAs/GaAs HFET devices.

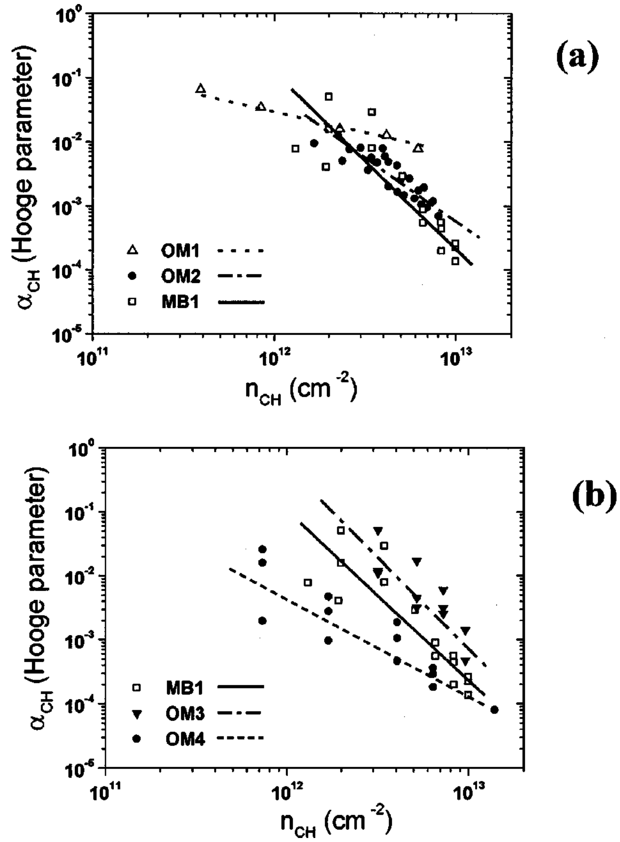

FIG. 2. Dependence of the Hooge parameter on the charge in the channel, α_{CH} vs n_{CH}, for samples (a) OM1, OM2, MB1, and (b) OM3, OM4, MB1. Sample MB1 (on sapphire) shows a Hooge parameter as low as 2×10^{-4} at $V_{GS}=0$ V ($n_{CH}\approx1.05\times10^{13}$ cm^{-2}); and sample OM4 (on SiC) shows an even lower Hooge parameter $\alpha_{CH}\approx8\times10^{-5}$, at $V_{GS}=0$ V ($n_{CH}\approx1.39\times10^{13}$ cm^{-2}). Lines are best fits to the experimental data (symbols).

Using Eq. (2), a strong dependence of α_{CH} on the number of carriers in the channel was found in all devices, following a power-law dependence, $\alpha_{CH}\propto(n_{CH})^{-\beta}$. However, the exponent β varies from sample to sample. Decreasing the number of carriers in the channel (by varying the gate voltage) produces an increase in the Hooge parameter. A model in which $1/f$ noise is generated by mobility fluctuations is proposed to explain the correlation between α_{CH} and n_{CH}. Previously it has been reported that the effect of the dislocation density on the carrier mobility of bulk structures and on the electrical characteristics of photoconductor GaN devices is very important.[10,11] We propose that fluctuations in the rate of trapping charge at dislocations modulates the carrier mobility (μ_T), due to fluctuations either in the carrier scattering rate or in the width of the depletion region surrounding dislocations.[12] Therefore, assuming mobility fluctuations, the total mobility fluctuates ($\delta\mu_T$) due to fluctuations in the term of the mobility limited by dislocations ($\delta\mu_d$). From Matthiessen's rule, the relation between $\delta\mu_T$ and $\delta\mu_d$ is extracted assuming that the contribution of the noise generated at dislocations (α_d) is much higher than the contributions from the lattice or interface roughness mechanisms. It is deduced that

$$\frac{S_{V_{DS}}}{V_{DS}^2}=\frac{S_{\mu_T}}{\mu_T^2}\approx\left(\frac{\mu_T}{\mu_d}\right)^2\frac{S_{\mu_d}}{\mu_d^2} \tag{3}$$

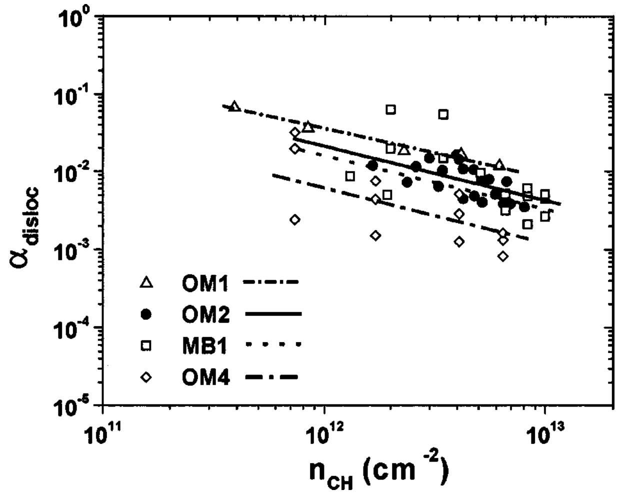

FIG. 3. Hooge parameter (α_d) of noise sources related to dislocations, calculated from α_{CH} assuming mobility fluctuations as the origin of noise. A power-law dependence of α_d vs n_{CH} is obtained, $\alpha_d \propto (n_{CH})^\beta$, with $\beta \approx -1$ for all devices.

and therefore, the Hooge parameter associated with the Coulomb scattering between carriers and dislocations (α_d) contributes to α_{CH} with a factor $(\mu_T/\mu_d)^2$

$$\alpha_{CH} \approx \alpha_d \left(\frac{\mu_T}{\mu_d} \right)^2. \quad (4)$$

This weighting factor was calculated from our transport data. In Fig. 3 the Hooge parameter associated with noise sources at dislocations (α_d) is plotted with the weighting factor included. This shows that α_d is still a function of the number of carriers, following a power-law dependence. An important result is that the exponent of this power-law is now the same for all the samples, ≈ -1. This dependence between α_d and n_{CH} suggests that the carrier screening effect is not only affecting the mobility but also the strength of the noise mechanisms.[13] The origin of the $1/n_{CH}$ dependence has been previously reported.[14] It was asserted that, in the case of discretely distributed scattering centers having $1/f$ noise in their cross-section, the $1/n_{CH}$ dependence comes from the carrier density dependence of the Debye screening cross-section.[14] Similar arguments can be extrapolated to justify our results.

As a first approximation, it can be assumed that α_d is proportional to the density of dislocations. In Fig. 3, α_d of sample OM4 (on SiC substrate) shows the lowest noise level. Therefore, this sample should have the lowest dislocation density. This result is complemented with the fact that OM4 also shows the highest charge in the channel. Generally, it is experimentally found that with the same design parameters, AlGaN/GaN devices grown on SiC have more two-dimensional charge than those devices grown on sapphire substrates. The lattice mismatch between SiC and GaN is smaller than sapphire and GaN, so one might expect the dislocation density to be lower.

In conclusion, the $1/f$ noise behavior of AlGaN/GaN heterostructures has been studied in devices grown on both sapphire and SiC by either metalorganic vapor phase epitaxy or MBE. A Hooge parameter as low as $\alpha_{CH} \approx 8 \times 10^{-5}$ was measured for HEMTs grown on SiC. A strong dependence of the Hooge parameter on the channel sheet carrier density was reported. To explain such a dependence, a model in which mobility fluctuations are generated by dislocations is introduced and the Hooge parameter associated with noise sources at dislocations have been determined.

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