Low-frequency noise in Al$_{0.4}$Ga$_{0.6}$N thin films (50 nm) was measured at room and elevated temperatures as function of gate and drain voltages. Both 1/f noise and generation-recombination noise were observed. Hooge parameter, $\alpha$, was estimated to be about 7. The activation energy for observed generation-recombination noise was found to be $E_a \approx 1.0$ eV. This activation energy is consistent with the activation energy observed for $g$-$r$ noise in AlGaN/GaN HFETs.

Keywords: AlGaN thin films; low frequency noise; 1/f noise; generation-recombination noise; activation energy.

1. Introduction

GaN, InN, AlN and their ternary alloys have been extensively investigated in recent years because of their potential microwave, and optoelectronic applications. GaN/AlGaN Heterostructure Field Effect Transistors (HFETs) have already demonstrated impressive results in high frequency and high power electronics [1-3].

Low frequency noise (LFN) is one of the most important characteristics of FETs, which determines the suitability of devices for microwave communication systems. The LFN noise properties of GaN layers and GaN based devices have been studied very intensively during the last several years (see [4] and references therein). Both 1/f and generation-recombination (GR) were found in GaN layers and AlGaN/GaN HFETs. The
temperature dependence of the GR noise reveals the activation energy of the local levels contributing to noise. At elevated temperatures the activation energy within the range from 0.35 to 1.0 eV were found in the AlGaN/GaN HFETs [4]. In Ref. [5] the GR noise with very small activation energy of $E_a=1-3$meV was pronounced at cryogenic temperatures (also in the AlGaN/GaN HFETs). In GaN GR noise is weak compared to the 1/f noise [6]. Therefore, the comparative studies of the low frequency noise and particular GR noise in AlGaN layers can be very useful for identification the origin of the GR noise in HFETs.

In this paper, we present experimental data on the low-frequency noise (1/f and GR) in thin Si-doped n-type AlGaN films and compare the results with the results of low frequency noise in AlGaN/GaN HFETs.

2. Experimental Details

Al$_{0.4}$Ga$_{0.6}$N thin films were grown at 1000 °C and 76 torr by low pressure Metal Organic Chemical Vapor Deposition (MOCVD) on sapphire substrate. A 50 nm AlN buffer layer was followed by the deposition of a 1 μm insulating AlGaN layer and a 50 nm n-AlGaN layer with the doping level of approximately $5 \times 10^{18}$ cm$^{-3}$. We used e-beam deposited Ti/Al/Ti/Au (100 Å / 300 Å / 200 Å /1000 Å) layers for ohmic contacts. These contacts were annealed at 850 °C for 60 s using Rapid Thermal Annealing (RTA) in nitrogen ambient. Helium ion implantation was used to isolate devices.

Low-frequency noise was measured in the frequency range from 1 Hz to 100 kHz in the temperature interval from 300 K to 550 K. The voltage fluctuations were measured using the ungated Transmission Line Model structures (TLMs) with $W=200$ μm width and distance, $L$, between the TLM pads ranging from 2μm to 20μm.

![Fig. 1. Doping profile extracted from capacitance-voltage measurements at 10 and 100kHz. The inset shows the gated TLM structure.](image-url)
3. Results and Discussion

The photoluminescence measurements of the AlGaN films showed the maximum of the light emission with the photon energy $E_{ph} \approx 4.5$ eV. This value is consistent with the band-gap of Al$_{0.4}$Ga$_{0.6}$N.

To find thickness and doping level of the Al$_{0.4}$Ga$_{0.6}$N layers the capacitance-voltage (CV) measurements were performed at frequencies from 1 kHz to 10KHz on the test Schottky diodes of the gated TLM structures with the area of $4 \times 10^{-4}$ cm$^2$ (see inset in Fig.1). Fig.1 shows the doping profile extracted from measurements at two frequencies. Those values are in agreement with the estimated values from growth parameters.

Measurements of the current-voltage characteristics on the TLM structures revealed contact resistance $R_C=240 \ \Omega \cdot \text{mm}$ and sheet resistance $R_{sh}=1.5 \times 10^4 \ \Omega$/square. Therefore even for the biggest distance of $L=20 \ \mu$m between pads in TLM structures the resistance of the layer was comparable with the contact resistance. The drift electron mobility estimated from the TLM and CV measurements was $\mu=20-30 \text{cm}^2/\text{Vs}$.

Figure 2 shows the noise spectrum for $L=20 \ \mu$m at room temperature. As seen, both 1/f noise and generation-recombination (GR) noise were observed.

Symbols in Fig. 3 show experimental dependence of noise measured at frequency $f=1\text{Hz}$ as a function of the distance between contact pads in the TLM structure.

Assuming that the noise sources are not correlated and located in the contacts and in the channel, the spectral noise density of the current fluctuations can be expressed as follows:

$$\frac{S_I}{I^2} = \frac{S_{RAlGaN}}{R_{AlGaN}^2} \frac{R_{AlGaN}^2}{(R_{AlGaN} + R_{SC})^2} + \frac{S_{Rsc}}{R_{SC}^2} \frac{R_{SC}^2}{(R_{AlGaN} + R_{SC})^2}$$

(1)

where $S_{RAlGaN}$ and $S_{Rsc}$ are spectral densities of channel resistance $R_{AlGaN}=R_{sh}L/W$ between contact pads, and total series contact resistance $R_{SC}=2R_C/W$ fluctuations, respectively.

![Fig. 2. Spectral density of low frequency noise at room temperature.](image-url)
In Eq. (1) first and second terms describe an increase and a decrease of the noise as function of $R_{AlGaN}$, respectively and represent the contribution from the AlGaN layer and contacts, respectively.

In order to calculate the first term in Eq.(1) we assumed that $S_{R_{AlGaN}}/R_{AlGaN}^2 \propto A$, where $A$ is the sample area. That complies with the common expression for the GR noise [7] and with the Hooge formula $S_{R_{AlGaN}}/R_{AlGaN}^2 = \alpha/(Nf)$, where $N$ is the total number of conduction electrons in the sample, $f$ is the frequency, and $\alpha$ is dimensionless Hooge parameter [8]. Due to the high contact resistance $R_{SC} > R_{AlGaN}$, contribution from the AlGaN layer increases with the distance $L$ between contacts pads, which is different dependence form the reported one for the GaN thin films with low contact resistance [9].

In order to calculate the second term in Eq.(1) we need to know $S_{R_c}/R_{SC}^2$. As follows from Eq. (1), when $L$ approaching, zero only contacts should contribute to noise. Therefore extrapolating the experimental dependence to $L=0$ should yield the value of $S_{R_c}/R_{SC}^2$.

By re-plotting the dependence shown in Fig.3 in the linear scale and extrapolating to $L=0$ we found $S_{R_c}/R_{c}^2 \approx 10^{-10}$ Hz$^{-1}$ at $f=1$ Hz.

In order to characterize the noise amplitude in terms of $\alpha$ values, $N$ is can be taken from the capacitance voltage measurements and sample dimensions. Since all resistances are known from the dc TLM measurements the value of $\alpha$ is the only fitting parameter in Eq.(1).
Dashed and dotted curves in Fig.3 are the results of the calculation of the first and second terms in Eq. (1) respectively. Solid curve in Fig. 3 is the sum of the two noise components. In order to fit the experimental data we set $\alpha=6$. As seen from Fig.3 there is qualitative agreement between experimental and calculated curves assuming the bulk origin of noise. Therefore, in spite of the large contact resistance, contacts do not contribute much to noise.

Figure 4 shows the temperature dependence of the noise spectral density $S_{\text{I}}/I^2$ at a series of frequencies. In the temperature interval between 400 and 450K, these dependences exhibit a clear maximum. The temperature $T_{\text{max}}$ corresponding to the maximum noise increases with frequency. This dependence is typical for the generation-recombination noise caused by a local level [10-12]. The sharp decrease of noise at temperatures 300-350K indicates the contribution to noise from another local level.

Figure 5 shows the dependencies of $1/kT_{\text{max}}$ versus $\ln (f)$ (the Arrhenius plots). The slope of this dependence gives the activation energy $E_a=1\text{eV}$. That is the same value as was found before for AlGaN/GaN HFETs [13] produced in the same process as AlGaN layers under investigation, even though the molar fraction of Al in those HFETs was lower ($x=0.2$).
In thin layers, GR noise might originate from a surface level. If the concentration of that level is high enough, then this level determines the position of the Fermi level at the surface (Surface Fermi level pinning). In this case, the parameters of surface level can be determined from the noise data as well [14]. Let us first estimate what is the minimum concentration of that surface level in order to satisfy the electro-neutrality condition:

\[
\frac{d\sigma_{NFN}}{dt} = 0
\]

Here \( N_{ts} \) is the surface level concentration, \( \sigma \) is the width of the surface space charge region, \( \varepsilon \) is the semiconductor dielectric constant, \( \varepsilon_0 \) is the permittivity of vacuum, \( q \) is the electron charge and \( V_s \) is the surface potential. Taking \( F=0.5 \) and \( V_s=1.0 \) V we find \( N_{ts} \approx 1.5 \times 10^{13} \) cm\(^{-2}\).

In order to find the lower bound for \( N_{ts} \) from the noise measurements we can again assume \( F=0.5 \). Then as follows from the Eq. (7) of Ref. [14]

\[
N_{ts} = 4S_{max}N_{ts}^2t^2\pi fA
\]

That gives \( N_{ts} \approx 3 \times 10^{13} \) cm\(^{-2}\), in qualitative agreement with the previous estimate. Hence, the assumption of the surface location of noise sources lead to a rather high but still reasonable surface concentration.

Our estimate of the level concentration \( N_{ts} \) assuming bulk location of traps gives \( N_{ts} \approx 2.4 \times 10^{19} \) cm\(^{-3}\). Since this is a lower bound of the level concentration and it is about one order of magnitude higher than the doping level \( N_d \) the assumption of the bulk noise level location can be considered as unrealistic.
4. Conclusion

Low frequency noise in thin Al$_{0.4}$Ga$_{0.6}$N layers was studied within the temperature range from 300 to 520K. In spite of the high contacts resistance comparable with layer resistance contacts do not contribute much to noise. Both, 1/f and generation recombination noise were found. Generation recombination noise with the activation energy of 1 eV might be attributed to the surface level. The same activation energy was found before for GR noise in AlGaN/GaN HFETs. This confirms that sources of GR noise in AlGaN/GaN HFETs are related to AlGaN barrier layer (see [13]). A high extracted value of the Hooge parameter $\alpha \approx 6$ typical for disordered materials indicates low structural perfection of the AlGaN layer.

Acknowledgement

The work at RPI was supported by the Office of Naval Research, and the project was monitored by J. Zolper. The work at SET, Inc. was supported by ONR under contract N00014-01-C-0195 and monitored by Y.-S. Park. The work at USC was supported by the Ballistic Missile Defense Organization (BMDO) under Army SMDC contract DASG60-98-1-0004, monitored by Dr. Brian Strickland and Dr. Kepi Wu.

References

N. Pala et al.
