INVESTIGATION OF LOW-FREQUENCY NOISE IN AlGaN/GaN HEMT AT VARIOUS TEMPERATURES

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1. Introduction

GaN HEMTs are generally accepted as a superior candidate for the next generation of wireless and high power electronic circuits due to their superior properties as reasoned not only from the published scientific papers, but also from complete RF and microwave amplifiers which are already commercialized. Even low phase noise non-linear circuits such as oscillators, highly sensitive to low-frequency (LF) noise level have been successfully designed [1]. Unfortunately, despite all of the advantages provided by GaN HEMTs and accomplishments reached by their applications the long-term reliability is still not sufficient and needs to be optimized [2], [3].

The LF noise analysis is well accepted for estimation of GaN HEMT structure quality, it is also an early indicator of device failure [3]. Since defects forming discrete energy levels in the forbidden band gap are able to trap electrons or operate as recombination centers, LF noise analysis allows to determine the nature of the traps from which originates the G-R noise [4], [5].

In this paper, we report on the investigation of the gate and drain low-frequency noise spectral density in AlGaN/GaN HEMT transistors grown on sapphire substrates. The effects of HEMT transistors operation point and temperature excitation in a temperature range from 25°C to 325°C on particular low-frequency noise sources were studied. We have found that the noise level and spectra are temperature dependent which could be attributed to deep levels in the forbidden band. The activation energies of the traps were extracted from the noise spectra taken at different temperatures using the Arrhenius dependence.

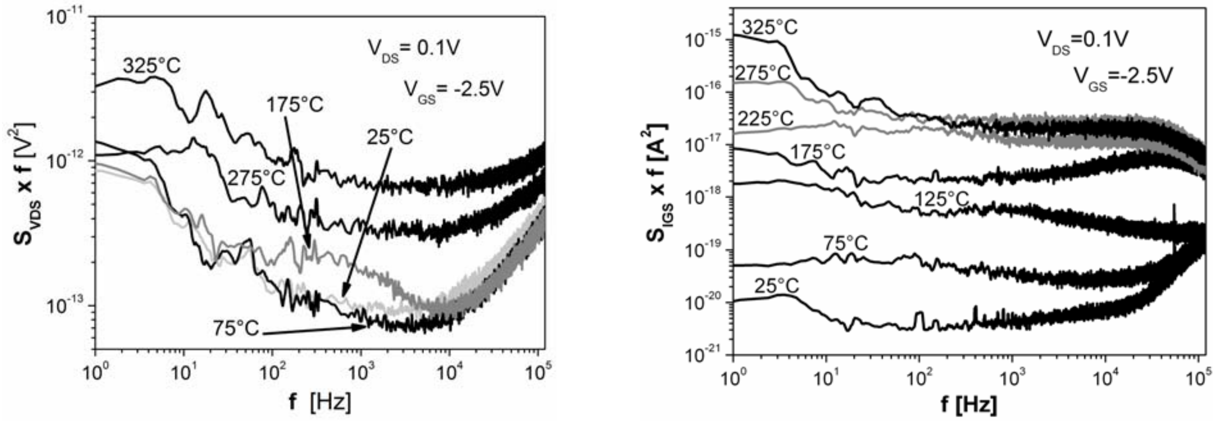
2. Experimental

HEMT transistor structures were grown on a sapphire substrate by MOCVD. The epitaxial structure consists of a 3 μm GaN:Fe buffer layer followed by 8 nm AlGaN, 6 nm GaN and 8 nm undoped AlGaN layers. Device processing of HEMT transistors started with Ar reactive ion etching for mesa insulation. Optical lithography was used to define Ti/Al/Ni/Au ohmic contacts and 2 μm long and 50 μm wide Schottky barrier Ni/Au gates. The distance between the drain and source is 6 μm.

LF noise measurements at room temperature were accomplished in a common source configuration with a 470 Ω resistor in series with the drain and V_{DD} voltage source. The spectrum of the output voltage noise from the drain amplified by an 80 dB voltage low-noise preamplifier with 4 nV/√Hz input noise was measured by an adapted signal spectrum analyzer based on a Σ/Δ analog-digital converter AD7760 in the 0.6 Hz - 120 kHz frequency range. Measurement software has been created in LabView. The output voltage noise measurements were accomplished in the linear and saturation regions of the HEMT transistors. For the input LF current noise measurements, the gate current was converted to voltage and pre-amplified by a low-noise current preamplifier SR570 with 2 pA/$\sqrt{\text{Hz}}$ input noise. The investigated DUT was heated by a designed control block based on NI 6008 data acquisition system supplemented with a thermocouple conditioning circuit and power IGBT used for driving the heating elements located in the shielded chamber. A conventional low-noise laboratory DC power supply was used for biasing of the heaters.

3. Results and discussion

To deeply investigate the nature of LF noise in HEMT structures, LF noise spectra were taken from the investigated devices at V_{DS}=0.1 V and V_{GS}=–2.5 V in the temperature interval from 25 to 325°C with a 50°C step. It has been confirmed that the operation point, mainly V_{DS} and I_{GS}, of the investigated transistors was temperature dependent as a result of carrier generation.



a) *b)*

Fig. 1: *The evolution of (a) drain voltage noise and (b) gate current noise of AlGaN/GaN HEMT in the temperature range from* 25°C *to* 325°C.

The temperature dependences of the corresponding drain voltage noise and gate current noise spectra are shown in Figs. 1a and b, respectively. The increase of the temperature influenced both the shape and the level of the measured LF noise spectra. The level of the measured input and output LF noise was the lowest at 25°C. The level of the measured LF noise spectra increased with every 50°C step. For the given temperature range the level of output LF noise spectra increased by one order and the level of input LF noise spectra increased by five orders. This indicates a strong temperature dependence of the input (gate) LF noise of measured AlGaN/GaN HEMTs. The level of drain noise spectra exhibited the highest increase at temperatures 275°C and 325°C. Interestingly, the level of the input noise spectra at these temperatures exhibited the smallest change as can be seen in Figs. 1a and 1b, respectively.

The measured drain LF noise spectra consist of 1/f and three, temperature almost independent G-R noise sources with characteristic frequencies approx. 8 Hz, 400 Hz and 120 kHz. The G-R noise source located at 120 kHz cannot be clearly seen because it is partially beyond the scale of the plot. Output LF noise measurements conducted at 125°C and 225°C are not displayed in order to increase the clearance of Fig. 1a. The measured gate LF noise spectra consist of 1/f noise and one dominant G-R noise source with temperature dependent characteristic frequency rising up from 5 Hz to 60 kHz in the given temperature range. To separate the G-R noise sources from pure 1/f noise, the measured noise spectral densities were multiplied by frequency so that every bulge on the *S(f)* × *f* curve represents the G-R noise source.

Assuming the total measured noise generated by uncorrelated noise sources, the noise power spectrum density can be expressed as

$$S_I = A + \frac{C}{f^n} + \sum_{j=1}^{m} \frac{D_j \tau_j}{(1 + (2\pi f \tau_j)^2)} \tag{1}$$

where f is the frequency and constants A, C and D_j represent the amplitudes of the shot and temperature, 1/f, and G–R noise sources, respectively. Exponent n represents the slope of the 1/f noise component. For GaN HEMTs it is in the range 1 to 1.3. The third term describes trapping and emission of carriers by m distinct traps characterized by specific time constants τ_j. In essence, τ_j characterizes a particular trap or deep level resulting in G-R noise of the typical spectrum with a plateau below and $1/f^2$ decrease above the corner frequency $f_c = 1/2\pi\tau_j$, respectively [5]. It has been shown that τ_j is proportional to T and E_a [7]:

$$\tau_j = T^{-2} \exp\left(\frac{E_a}{kT}\right) \tag{2}$$

where E_a is the trap activation energy, T is temperature and k (1.38×10^{-23} JK^{-1}) is the Boltzmann constant. Detailed analyses have been made by several authors [7], [8]. From Eq.(2) the Arrhenius plot can be directly drowned showing ln$(\tau_j T^2)$ *versus* q/kT for several values of τ_j obtained from the measured LF noise spectra at different temperatures. The slope of the curve fitting all obtained points for a particular G-R noise source gives the activation energy of the trap causing the particular G-R noise. The measured LF noise spectra in Fig. 1 are displayed as a spectral noise density *S(f)* × *f* versus frequency *f* at different temperatures, where every bulge on the noise spectra represents the G-R noise [6]. Hence, the characteristic time constant of G-R noise spectrum τ_j at different temperatures was directly acquired from the dependence *S(f)* × *f*.

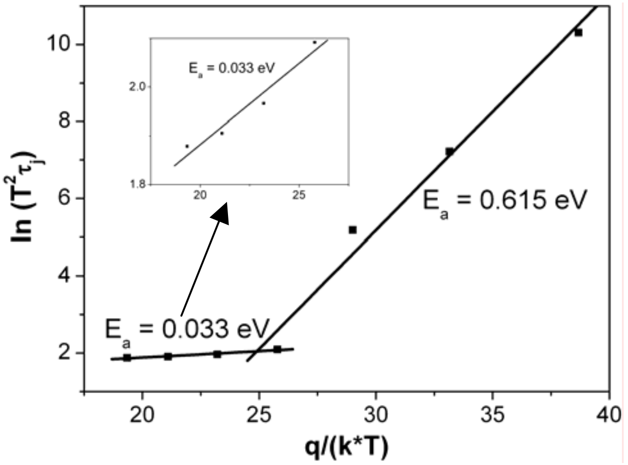


Fig. 2: *The Arrhenius plot extracted from input LF noise measured in temperature range from* 25 *to* 325°C.

The characteristic time constants of G-R noise for various temperatures were extracted form the input and output LF noise spectra. The activation energy obtained from the output LF noise spectra was approx. ~50 meV, very close to the *kT/q* resolution limit, so it could be neglected. It is well known that accuracy of the determination of the activation energy from the Arrhenius plot is strongly dependent on the accuracy of the τ_j values, where a change in τ_j by a factor of two results in an E_a error of 10% [6]. The Arrhenius plot constructed from the τ_j values extracted from the input LF noise is shown in Fig. 2. The slopes of the linear fit for each trap led to activation energies 0.615 eV and 0.033 eV. Comparison of the extracted activation energies indicates similarity with energies published already for the AlGaN/GaN system [7]. It has to be mentioned here that LF noise measurements cannot give a very accurate trap activation energy like for instance DLTS because of the stochastic nature of the noise itself.

4. Conclusion

The study of low-frequency noise in AlGaN/GaN HEMTs in the temperature range from 25 to 325°C indicates an important contribution of the traps especially to the gate noise of the structures. In the output low-frequency noise spectra, a one order increase was observed in the amplitude of both 1/f and generation-recombination noise with a stable characteristic time constant for a given temperature range. In the input low-frequency noise a five order increase was observed of the level of low-frequency noise spectra and a change of the characteristic time constant of generation-recombination noise. Activation energies E_a=0.615 eV and E_a=0.033 eV were found from the evolution of the temperature dependant G-R noise in the input low-frequency noise spectra. The obtained activation energies indicate that at temperature ~175°C the nature of the trap is changing which causes G-R noise.

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