Figures of merit in high-frequency and high-power GaN HEMTs

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Abstract

The most important metrics for the high-frequency and high-power performance of microwave transistors are the cut-off frequency $f_T$, and the Johnson figure of merit $FoM_{Johnson}$. We have simulated a state-of-the-art, high-frequency and high-power GaN HEMT using our full band Cellular Monte Carlo (CMC) simulator, in order to study the RF performance and compare different methods to obtain such metrics. The current gain as a function of the frequency, was so obtained both by the Fourier decomposition (FD) method and the analytical formula proposed by Akis. A cut-off frequency $f_T$ of 150 GHz was found in both the transit time analysis given by the analytical approach, and the transient Fourier analysis, which matches well with the 153 GHz value measured experimentally. Furthermore, through some physical considerations, we derived the relation between the $FoM_{Johnson}$ as a function of the breakdown voltage, $V_{BD}$, and the cut-off frequency, $f_T$. Using this relation and assuming a breakdown voltage of 80 V as measured experimentally, a Johnson figure of merit of around $20 \times 10^{12}$ V/s was found for the HEMT device analyzed in this work.

1. Introduction

Several figures of merit are often used to evaluate the performance of microwave devices. The most important metrics for the high-frequency and high-power performance of microwave transistors are the cut-off frequency, $f_T$, and the Johnson figure of merit, $FoM_{Johnson}$ [1]. The cut-off frequency is related to the short circuit current gain, $h_{21}$, which is defined as the ratio of the small-signal output current to the small-signal input current of the device when the output terminals are shorted. The Johnson figure of merit takes into account the breakdown electric field, $E_{BD}$, and saturated electron drift velocity, $v_{sat}$, in defining a measure for the power handling capability at high frequencies.

We have simulated a state-of-the-art, high-frequency and high-power GaN HEMT, reported by Palacios et al. [2], using our full band Cellular Monte Carlo (CMC) simulator, in order to study the RF performance and compare with the prediction of the analytical model for the cut-off frequency calculations proposed by Akis et al. [3]. Furthermore, through some physical considerations, we derived the relation between the $FoM_{Johnson}$ in function of the breakdown voltage $V_{BD}$ and the cut-off frequency $f_T$. Using this equation, the Johnson figure of merit can be connected directly to microwave measurements in a meaningful manner and calculated easily by standard experimental measurements.

2. GaN HEMT with InGaN back barrier

The layout of the device described in this work is composed of an AlGaN/GaN heterostructure with an InGaN back barrier grown on a semi-insulating SiC substrate by metal-organic chemical vapor
deposition. The heterostructure is unintentionally doped and consists, from bottom to top, of 1.5µm of GaN followed by 1nm of In0.1Ga0.9N capped by 11nm of GaN and 25nm of Al0.32Ga0.68N as shown in Figure 1. The AlGaN layer is recessed in order to have a gate-to-channel distance of 13nm. The source-gate and gate-drain separations are both 0.75µm, while the gate length is set to 0.1µm. Highly doped regions are created under the source-drain electrodes down to the GaN channel to emulate metal spikes and to control contact resistances.

The presence of the InGaN layer enhances the confinement of the electrons in the channel. In fact, the large polarization-induced electric field in the InGaN layer raises the conduction band edge of the GaN buffer with respect to the GaN channel, creating a potential barrier against carrier diffusion in the bulk layer. More details on that device can be found in [3], where all the characteristics of the sample used to obtain the experimental data are reported.

3. RF analysis of AlGaN/GaN HEMT

The basic idea of the small-signal frequency, or RF, analysis consists of applying a small perturbation to one electrode of the device in steady-state, while keeping all other parameters constant. The small-signal parameters can then be derived from the Fourier analysis of the transient response. The response in the transient regime is a function of the device characteristics, such as the geometry, the doping profile, the transport properties of the device and the steady-state operating point (i.e. the DC components of $V_{DS}$ and $V_{GS}$).

In our study, the operating point for the RF analysis ($V_{GS} = 0V$, $V_{DS} = 6V$) has been chosen in order to compare simulation results with experiment [2]. The current gain as a function of the frequency is shown in Figure 2. The right plot, representing the simulation results, is obtained by the Fourier decomposition (FD) method, where a small step voltage is applied to the input port of the device in steady state, and the transient short circuit current response is Fourier analyzed to obtain the cut-off frequency.

4. Cut-off frequency

An alternative method to calculate the current gain cut-off frequency, $f_T$, is to relate this to the transient time at carriers across the effective gate length [3]:

$$f_T = \left[ \frac{1}{2\pi} \int_{L_{eff}} \frac{1}{v_{ave}(x)} dx \right]^{-1}, \tag{1}$$

where $L_{eff}$ is an effective gate length and $v_{ave}(x)$ is the average simulated velocity along the channel.

The simulated electron drift velocity profile along the channel used in the calculation of the cut-off frequency according to Eq. (1) is illustrated in Figure 3.
A cut-off frequency $f_T$ of 150 GHz was found in both the transit time analysis given by Eq.(1), and simulation results using transient Fourier analysis, which matches well with the 153 GHz value measured experimentally [2].

5. Johnson figure of merit

In general, widebandgap materials like GaN have desirable properties for high power applications due to their large band gap and high thermal conductivity. The Johnson figure of merit mentioned earlier, characterizes the high frequency performance of power devices, and is proportional to the saturation velocity and critical electric field for impact ionization initiated breakdown [1]

$$F_{oM_{Johnson}} = \frac{v_{sat} E_{BD}}{2\pi},$$

where $v_{sat}$ is the saturation velocity and $E_{BD}$ is the electric field at which impact ionization initiates breakdown. Unfortunately, this figure of merit is difficult to determine experimentally as both $v_{sat}$ and $E_{BD}$ are intrinsic properties of a device, although easily found from simulation. However, these quantities can be connected to microwave measurements in a meaningful manner. Generally, the cutoff frequency, $f_T$, is related to the effective saturation velocity through the well-known formula

$$f_T = \frac{v_{sat}}{2\pi L_G},$$

where $L_G$ is the gate length (or effective gate length). We also find from detailed simulations, that the field under the gate varies almost linearly over the length of the effective gate. Breakdown usually occurs near the drain end of the gate, where the highest field occurs. Since there is also a potential drop across the space between the gate and the contacts, we can write the breakdown voltage in terms of the breakdown field as

$$V_{BD} = \alpha \frac{E_{BD} L_G}{2}$$

where $\alpha$ is an adjustable parameter that relates the voltage drop across the gate to the total voltage applied to the device. Hence, we can rewrite the figure of merit in terms of these experimentally determined parameters as
Figure 3. Electron drift velocity profile along the channel resulting by the CMC simulation

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F_{oM, Johnson} = \frac{1}{2\pi} \left( \frac{2\pi L_G f_T}{\alpha L_G} \right)^2 \frac{2V_{BD}}{f_T V_{BD}} = \frac{2}{\alpha} f_T V_{BD}.
\]  

The \( \alpha \) parameter can be extracted directly from the simulations using Eq. (4), and calculating the breakdown voltage as an integral of the field across the channel when the impact ionization first occurs.

Using a value previously published for GaN for Eq. (2) [4], and values found in simulations of GaN HEMTs, we find that \( \alpha \) is appropriately 1.25, although this factor could be ignored without much loss of relevance of the figure of merit since its close to unity. Following Eq. (5) and assuming a breakdown voltage of 80V [2], a \( F_{oM, Johnson} \) around \( 20 \times 10^{12} V/s \) was found for the HEMT device analyzed in this work.

6. Conclusion

In this paper, the most important metrics to evaluate RF performance of GaN HEMT devices were investigated, through comparison between experimental, simulation and analytical method. The Fourier decomposition method was used to evaluate the cut-off frequency in our full band CMC simulation code, which includes the full details of the band structure and the phonon spectra. Thermal simulations were performed with commercial software in order to determine the corrections needed to model thermal effects with our particle-based CMC simulator. Our studies indicate that both the transit time analysis given by Eq.(1), and simulation results using transient Fourier analysis, matches well with the experimental data. We also derived an analytical model to determine the Johnson figure of merit and extracted this quantity from standard experimental data.

References

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