An athermal measurement technique for long time constants traps characterization in GaN HEMT transistors.

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Abstract

GaN High Electron Mobility Transistors (HEMTs) are very promising for high power switching and radiofrequency operation. However, the lack of reliability feedback is one of its major drawbacks. Trapping effect especially is one of the main performance limitations of such components. Many measurement techniques exist for trapping effects characterization, especially for short time constant traps (μs to several ms). However for longer time constants, self-heating may distort the measurements. This paper presents an electrical and athermal transient measurement method which has been developed to study the trapping and detrapping time constants of such components. It allows the extraction of slow transients without self-heating problems and is usable in long term electrical stress experiments. A simulation of this method with a simplified component's model and the measurements results are presented. With this technique, we investigated especially the long time constants ($\tau > 20$ ms) over a range of temperature from 10°C to 105°C . We observed three thermally activated trap signatures on GaN devices with our method.

Keywords- slow transients, traps, GaN, High Electron Mobility Transistors (HEMTs).

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1. Introduction

Wide band gap semiconductor devices such as AlGaIn/GaN High Electron Mobility Transistors (HEMT) are promising for RF power and high-voltage switching applications [1]. However, the main limitation of its performance is the trapping effect, appearing before and during its operating lifetime [2, 3, 4]. One of its principal consequences is the current collapse: a recoverable reduction in drain current after the application of a high voltage. These trapping effects in GaN HEMTs have a slow nature. The recovery time from current collapse can be slow for these devices (>100s to several days) [3, 5, 6]. This phenomenon is thus critical in the component's applications i.e. RF systems or power electronics.

A variety of techniques already exist in order to measure this phenomenon like C-DLTS [7] but this technique is not always suitable for studying this kind of semiconductor devices [8, 9]. The capacitances are very small and have to be measured in a short time. The other existing techniques like I-DLTS, DLOS or low frequency noise measurements [10, 11, 12, 13] give a lot of information but - as DLTS - are not easily incorporated in long-term electrical stress experiments. Some methods such as transient measurement are promising for their use in long-term electrical stress [8, 14] but self-heating effects may distort the signal even for relatively low currents. A correction of this effect is possible using the thermal resistance [15].

In this paper, we present an alternate way of characterizing the trapping time constants without thermal effects. This athermal transient measurement technique is used to analyze the slow detrapping ($\tau > 20\text{ms}$) behavior of GaN HEMTs and is usable in integration with long-term stress experiments. This method allows a measurement in the saturation or ohmic region without self-heating problems.

2. Methodology

Our method consists in a transient measurement in pulsed mode between two equilibrium states (figure 1) in order to study slow transients in the saturation or ohmic region by limiting the occurrence of self-heating. The principle is similar to pulsed IV measurement: the pulses length is fixed at $2\text{ }\mu\text{s}$ (in order to have a stable current in the pulse) with a duty cycle of 0.2%. Self-heating may occur at $t < 1\text{ }\mu\text{s}$ but its highest effect is visible at longer times [16], due to the package and die thermal behavior. The signals on the drain and the gate are generated via an IV measurement bench from AMCAD Engineering. The image of the drain current is then retrieved using the voltage drop of a shunt resistance of low value ($0.5\text{ }\Omega$). In order to only extract the current in the pulses, we developed an electronic card with instrumentation amplifiers and a sample and hold circuit. The signal is then retrieved using a NI USB - 4431 acquisition card (figure 2).

Regarding the span of the transient (from several microseconds to 1000s), the use of the sample and hold device does not distort the signal.

Fig. 1. Methodology of measurement: Signal applied on the gate of the transistor. The drain bias is fixed at 10 V or 0.5V (ohmic or saturation zone).

Fig. 2. Methodology for the measurement of a slow current transient in pulsed mode. Inset shows the Vgs and Ids level in the component, with the use of sample and hold. $V_d=10V$ or $0.5V$.

The transistor is first pulsed from an OFF-state level at $V_{gs} = -8V$, the high level being at $V_{gsh} = -1V$, $-1.9V$ (close to the pinch-off) or $0V$ and the drain bias is fixed at $V_d = 10V$ or $0.5V$ (ohmic or saturation zone). The trapping state is held for a relatively long period of time (500s), ensuring the same initial state for all measurements. This value has been defined based on trapping measurements (shift of V_{gs1} from $-3V$ to $-8V$ at a given V_{gsh}) with our technique (figure 3). When the equilibrium is attained, the device is pulsed from a less negative state, also below the pinch-off voltage at $V_{gs1} = -3V$ with the same V_{gsh} , ensuring the emission of traps by relieving the electric field in the structure (V_{gs1} is closer to $0V$, see figure 1). The measured detrapping time constants are then between several ms to 1000s (the maximum time is only limited by the number of points in the curve).

Fig. 3. Trapping transients in pulsed mode at $T=32.5^\circ C$ and $42.5^\circ C$ ($V_{gsh} = -1.9V$, $V_{ds}=0.5V$) and $77^\circ C$ for $V_{gsh} = -1V$, $V_{ds}=10V$. The trapping time is fixed around 500s to obtain the equilibrium.

The measurements are done in a range of temperature from $283K$ to $363K$ and the time constants are then extracted using a multiexponential model. For each temperature, we use the Prony algorithm, which indicates the number of defects in each transient (number of peaks and valleys). Furthermore, it brings starting parameters usable with the Levenberg-Marquardt algorithm in order to extract the corresponding time constants [17]. The time constants are then extracted by non-linear least square fitting.

The devices studied in this work are AlGaIn/GaN HEMTs powerbars on SiC substrate with a $0.5\mu m$ gate length and $25W$ output power (European technology).

3. Simulation of the measurement method

In order to be sure that the pulsed measurement doesn't interfere during trapping and detrapping, we developed a simulation of the component using ADS (Advanced Design System) from Keysight. The intrinsic current source is modelled through a hyperbolic tangent equation and adjusted in order to correspond with pulsed IV measurements on the transistor (figure 4.1). The thermal behavior is simulated via a thermal Ohm equation (figure 4.2):

$$T_j = Z_{TH} * P_{diss} + T_c \quad (1)$$

Z_{TH} is the thermal impedance given by:

$$Z_{TH} = \sum_i^n R_{THi} \left(1 - e^{-\frac{t}{\tau_i}}\right) \quad (2)$$

T_j is the junction temperature, T_c the case temperature, P_{diss} the dissipated power and R_{THi} the thermal resistance of each thermal junctions (for example AlGaIn/GaN, GaN/SiC, SiC/case) and $\tau_i = R_{THi} * C_{THi}$ are the thermal time constants, modelled with RC circuits. The R_{TH} and C_{TH} parameters are extracted using measurements of $I_{dss} = f(T_j, t)$. Two thermal junctions were necessary in order to reproduce the thermal behavior given by the self-heating measurements. The variation of $gm = f(T_j)$ using I_{dss} measurement with short pulses ($2\mu s$) was also extracted in order to complete the electro thermal model.

(4.1)

(4.2)

Fig. 4. Simplified model of the current source of the component (4.1) and thermal Ohmic law for simulating the thermal behavior of the component (4.2).

The trapping and detrapping phenomena are included using a model given by Jardel et al [18]. A little modification is done in order to include a feedback of the junction temperature (including self-heating effects) on the time constants values (figure 5). This temperature dependence in Arrhenius is set to values close to the time constants we measure (τ between several ms and 1000s, $E_a = 0.58$ eV).

Fig. 5. Modeling of trapping effects. The dependence of $\tau_i = R_i C_i$ is given by the Arrhenius's law.

The pulsed gate signal is then integrated at the entry of the circuit. The method was simulated from 10 to 90 °C and the trapping and detrapping time constants were retrieved with the signal envelope (figure 6). The simulated temperature rising in each pulse is below 0.4°C, the transistor being really in a stable thermal state due to the pulsed signal on the gate (with a 0.2 % duty cycle). The time constants extracted from simulated current transient (figure 6) are in agreement with the values included previously

in the model (figure 7) until $\tau < 20$ ms. Below this value, the length of the pulses distorts the output visible time constant. This result confirms the absence of interference of the pulses on the measured time constants for $\tau > 20$ ms as the pulses and thermal behaviour don't distort the output signal.

Fig. 6. Envelope of a simulated current transient (trapping and detrapping) at $T_j = 80^\circ\text{C}$. Inset shows the simulated temperature rising, which is below 0.4°C.

Fig. 7. Comparison between simulated and extracted values for trapping and detrapping phenomena.

We are then able to measure slow trapping and detrapping effects at any polarization, i.e. closer to standard current levels in the application, highly limiting thermal effects.

We also simulated the self-heating of the component for some of the polarization protocols used in the literature [2] for ON-state measurements. The high current levels induce critical self-heating ranging from $\Delta T = 27$ K for $V_{ds} = 10\text{V}$, $V_{gs} = 0\text{V}$ and

1s-pulse to $\Delta T = 15.6$ K for $V_{ds} = 6$ V, $V_{gs} = 1$ V and 1s-pulse (figure 8). The resulting thermal effect is then very important and will deform the activation energies extracted, confirming the need for an athermal measurement technique or a correction of its effects [15].

Fig. 8. Simulated self-heating effect of the component during ON-state filling pulse and ON-state trapping measurement.

The originality of this work is then to allow a trapping or detrapping measurement without self-heating effects, without restriction on power density.

4. Measurement results and discussion

The concept being validated with the simulation, we measured the detrapping time constants of several AlGaIn/GaN HEMTs on SiC substrate with different conditions: $V_{gs_{sh}} = -1.9$ V with $V_{ds} = 0.5$ V on one hand and $V_{gs_{sh}} = -1.9$ V, -1 V and 0 V with $V_{ds} = 10$ V on the other hand. Some examples of drain current transients at different temperatures are presented on figure 9.

Fig. 9. Examples of measured transients at different temperatures, the time is in logarithmic scale ($V_{gs_{sh}} = 0$ V, $V_{ds} = 10$ V). Two peaks and one valley are observed with this measurement protocol.

The measurements at $V_{gs_{sh}} = -1.9$ V (close to pinch-off) and $V_{ds} = 10$ V presented three trapping characteristics activated at different temperatures (figure 10). Two time constants representing peaks on the current transient (DP1 and DP2) at 0.45 eV (12s to 975s) and 0.65 eV (2ms to 48ms) and a valley (TP1) at 0.86 eV (150ms to 3s) were measured. These activation energies are associated to C/O/H impurities for DP1 [19], VGa Oxygen complex for DP2 [20] and gallium vacancies for TP1 [21] in the literature. The time and thermal windows for DP1 is notably in good concordance with the literature [19].

By changing $V_{gs_{sh}}$ to -1 V, some of the activation energies extracted are different (figure 11). DP2 is still visible in the same temporal and thermal window. The observation of this defect is then not dependent on the canal aperture. However, the valley TP3 and the highest peak DP3 are found respectively at 0.76 eV (15ms to 10s, activation energy associated to Nitrogen interstitials [22]) and 0.69 eV (1.5s to 900s, activation energy associated to surface traps [23]). A possible explanation of these differences may consist in considering that at $V_{gs_{sh}} = -1.9$ V, the device is close to pinch-off. The depletion region will stimulate relatively deep traps in the structure: close to the AlGaIn/GaN interface (due to its range) and buffer traps. Whereas at $V_{gs_{sh}} = 0$ V, there is no depletion. The stimulated defects will then have a tendency to be linked to the surface, the AlGaIn/GaN interface and the GaN buffer.

Fig. 10. Arrhenius plots of the measurement at $V_{gs_{high}} = -1.9$ V and $V_{ds} = 10$ V. Three defects are present.

Fig. 11. Arrhenius plot of the time constant extracted for $V_{gs_{sh}} = -1$ V and $V_{ds} = 1$ V.

The measurement protocol at $V_{gs_h}=0V$ gave the same activation energies giving the measurement precision. This indicates that when the canal is far from pinch-off during the pulse, the same traps are activated. It also shows that the temperature rising in the component is not high enough to interfere with the extraction, the current levels being higher when V_{gs_h} rises.

When biasing the component in the ohmic zone ($V_{gs_h}=0.5V$), the general behavior of the component is also different (figure 12). A trap in the temporal and thermal window of DP2 is visible (7ms to 0.3s, 15°C to 55°C). Its activation energy being close, it has been associated to DP2 (the two Arrhenius plots match each other). A valley with activation energy of 0.68 eV has also been observed (45ms to 14s, associated to surface traps [23]). Finally, the slowest peak presents an odd behaviour. Two activation energies may be extracted. A peak DP4 at 0.62 eV (480s to 2000s), which precision is not reliable because the time constants measured between 25°C and 40°C too slow for our recording window ($\tau > 1000s$). Between 35°C and 70°C, the detrapping behavior doesn't really change with the temperature. Then, starting from 75°C to 105°C, another activation energy DP5=0.72 eV can be extracted (200s to 800s). DP5 is associated to Fe dopant in the literature [24] but precision on the extraction is relatively low (0.07 eV). Furthermore, its temporal window in the literature is really different (53 μs to 35ms).

Fig. 12. Arrhenius plot of the time constant extracted for $V_{gs_h} = -1.9V$ and $V_{ds} = 0.5V$.

5. Conclusion

We presented in this work an athermal measurement technique for long time constant traps

characterization. This measurement is accomplished in pulsed mode (2 μs pulse, 0.2% duty cycle) between two equilibrium states. A trapping state pulsed between $V_{gs_l}=-8V$ and V_{gs_h} is maintained until equilibrium. Then, slow traps are released with a detrapping state pulsed between $V_{gs_l}=-3V$ and V_{gs_h} . The time constant extracted vary between several ms and 1000s.

The current source and thermal behaviour of the component were simulated from measurements. Thermal depending trapping effects were also added to the model. By reproducing our gate signal in the simulation, we extracted from the simulated current transient the right time constants, without self-heating distortion. The simulated temperature rise is below 0.4°C. Simulation in DC for measurement protocols used in the literature have shown significant temperature rise in the component.

Measurements with our technique at different voltages were carried out on AlGaIn/GaN HEMT devices. The various protocols (high electric field, open canal or close to pinch-off) permitted the extraction of a joint trap DP2 linked to gallium vacancies. When the canal is open, this method allows the extraction of surface traps and defects in the AlGaIn layer with a canal close to pinch-off.

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