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Third Order Notch over Multi-bias and Temperature in GaN and GaAs HEMTs

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Abstract — A detailed study about the shifting of third-order notch and threshold voltage with temperature for GaN and GaAs FETs were analyzed. For this purpose, a great deal of data over temperature between -40 to 150°C were measured by using two-tone intermodulation distortion set up. It was found that the third order notch current point exactly follows the trends of threshold voltage (V_T) shifting with temperature. The thermal response of V_T demonstrates a raising trend in GaN and a falling trend in GaAs FETs. An analytical model for notch current was developed and well validated with the measured data. This study represents some significant and thorough understanding to investigate the device behaviour.

Keywords — notch in third order IMD, threshold voltage, GaN and GaAs HEMTs, multi-bias and temperature.

I. INTRODUCTION

The GaN devices have picked up an enormous level of attention to appear as a promising candidate for high-power performances. Up to presently, it got to be the innovation of selection for the existing and forthcoming device technology due to its remarkable power handling capability in relation to the well-established GaAs based technology [1]. Owing to the wide band gap of GaN and the excellent thermal conductivity of SiC, their conjugation (i.e., GaN on SiC based devices) can preserve high electric field and high temperature [2]. Concurrently, GaAs is a sophisticated device technology with respect to good linearity, low noise, high power and high efficiency applications as well as good terminal contacts [3]. The threshold voltage V_T is a critical index and together with a leading factor for the other parameters of FETs operation [4]. It is an important issue to study the thermal behaviour of V_T and its impact on device nonlinearity especially the notch/null's point for this two-competitor semiconductor device technology. On the other hand, at the null's or notches current point in the non-linear components exhibits minimum distortion level. This null's or notches current point varies from processing conditions of sample to sample [5]. All of the non-linear intermodulation distortion (e.g., IMD) products reveal notches/nulls while operating at multi-bias condition. These notches/nulls are perhaps useful for the design of a distortion less amplifier with low noise [6]. The notch voltage exhibits a positive trend in GaN device and a negative trend in GaAs device in response to temperature following behaviour

of V_T . Meanwhile, both measured and simulated third order notch current of the two devices (GaN and GaAs) decreases with temperature. That substantial study of notch current in conjugate with V_T for GaN and GaAs HEMT will help the RF engineer to take into account all through the design and optimization strategy.

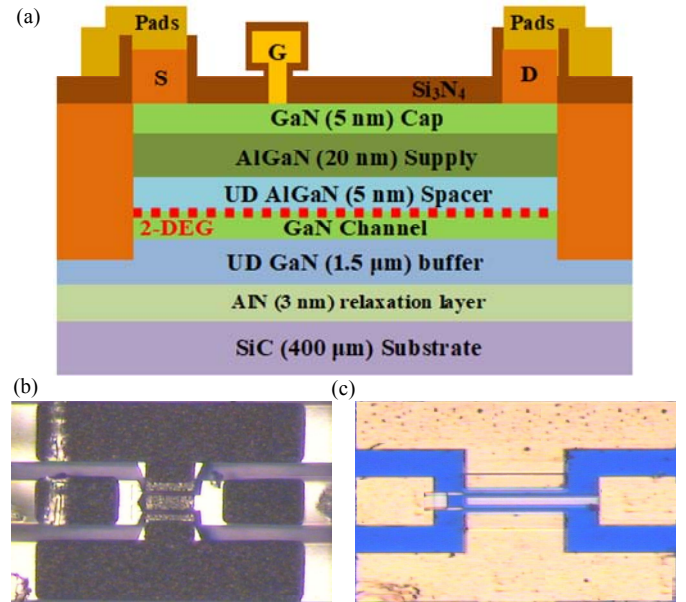


Fig. 1. a) The cross-sectional view of the studied GaN HEMT, (b). top view of the GaN HEMT and (c) top view of the GaAs HEMT.

II. EXPERIMENTAL AND THEORETICAL BACKGROUND

The AlGaAs/GaAs heterostructure is grown by molecular beam epitaxy (MBE) and the AlGaIn/GaN heterojunction is developed on SiC substrate utilizing metal-organic chemical vapor phase deposition (MOCVD) technology. The details of the epitaxial layer structure of the GaN HEMT is illustrated in Fig. 1 (a) while the epitaxial structure of the GaAs HEMT can be found elsewhere [7]. The gate dimensions of the double gate fingered GaN transistor is $(100\ \mu\text{m} \times 0.25\ \mu\text{m})$ and the GaAs transistor is $(200\ \mu\text{m} \times 0.5\ \mu\text{m})$. The top view of the studied GaN and GaAs transistors are presented in Figs. 1 (b) and (c), respectively. The computer program controlled two-

tone intermodulation distortion (IMD) measurement set-up gives an advantageous assessment especially when tremendous sums of data are essential to be analyzed. The IMD data was measured at the frequency f_1 of 2 GHz, with the separation of 1 MHz plus input and output matching over a 50 Ω load and source resistances. The applied temperature range was -40 to 150°C where the input power was 0 dBm.

The output current of a FET can be characterized from Curtice model in saturation region as follows [8]:

$$I_{ds} = \beta(V_{gs} - V_T)^2(1 + \lambda V_{ds})\tanh(\alpha V_{ds}) \quad (1)$$

where $V_{gs} = (2I_{ds} + g_m V_T)/g_m$, α (V^{-1}), and β (A/V^2), λ (V^{-1}), are the transconductance, tanh parameter and channel modulation, respectively at $V_{ds} > 0$, $V_{gs_peak} = V_{pf}$ and V_{pf} can be given as (the point of transconductance peak arise and starts falling) $V_{gs_peak} = (2I_{ds_peak}/g_{m_peak}) + V_T$. Rearranging this one can obtain the expression below:

$$I_{ds_peak} = \frac{1}{(V_{gs_peak} - V_T)^2} \frac{g_m}{2} \quad (2)$$

The output current at the null's point of the second-order IMD2 ($I_{ds_notch_IMD2}$) can be presented from the differentiation of eqn. (2) and reorganized:

$$I_{ds_Notch_IMD2} = - (V_{gs_peak} - V_T)^2 \frac{g_{m2}}{2} \quad (3)$$

In the same way, the output current at the null's point of the third-order IMD3 (e.g., $I_{ds_notch_IMD3}$) can be presented from the differentiation of eqn. (3) and reorganized:

$$I_{ds_Notch_IMD3} = - (V_{gs_peak} - V_T)^3 \frac{g_{m3}}{4} \quad (4)$$

when $(V_{gs} - V_T)$ is minimum in the expression (3)-(4), the G_{m2} (transconductance first-derivative) alters its phase from positive to negative values resulting in a notch or dip in IMD2 harmonic and the output current at this point is termed as $I_{ds_notch_IMD2}$. In the same way, when G_{m3} (transconductance second-derivative), goes from positive to negative values, a notch or dip will be raised in IMD3 harmonic and the output current at this point is termed as $I_{ds_notch_IMD3}$. Using the expressions (3) and (4) one can easily estimate the notch current of the nonlinear IMDs.

III. RESULTS AND ANALYSIS

A. Measured results of notch in third-order intermodulation distortion (IMD3) product for GaN and GaAs HEMTs

Measured third-order intermodulation distortion (IMD3) product against output current, I_{ds} showing notches over temperature using two-tone IMD set up for the GaN and GaAs HEMTs as illustrated in Figs. 2 and 3. The notch current in IMD3 is reduced from 26 mA to 18.85 mA in GaN HEMT while from 5.1 mA to 4 mA in GaAs HEMT approximately when the temperature rises from -40 to 150°C . The IMD3 plots against output current show that the notch current is declined with temperature likewise the thermal response of the output current I_{ds} [9] in both cases as presented in Figs. 4 and 5, respectively. The variation of both output current and notch current is higher in GaN HEMT compared to that of the GaAs

HEMT. It is well-known that the GaN semiconductor has higher band-gap and thermal conductivity than GaAs. In addition, the magnitude of IMD3 increases up to 63 mA at -40°C and up to 43 mA at 150°C and after that decreased in GaN HEMT.

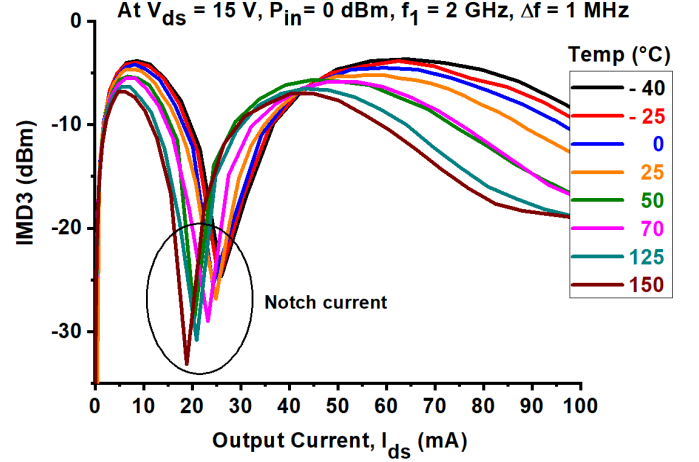


Fig. 2. Measured third-order intermodulation distortion (IMD3) product versus output current, I_{ds} showing notches over temperature for the GaN HEMT.

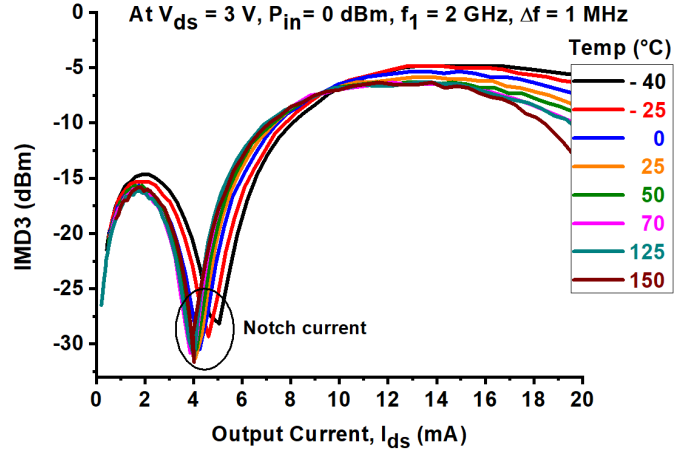


Fig. 3. Measured third-order intermodulation distortion (IMD3) product versus output current, I_{ds} showing notches over temperature for the GaAs HEMT.

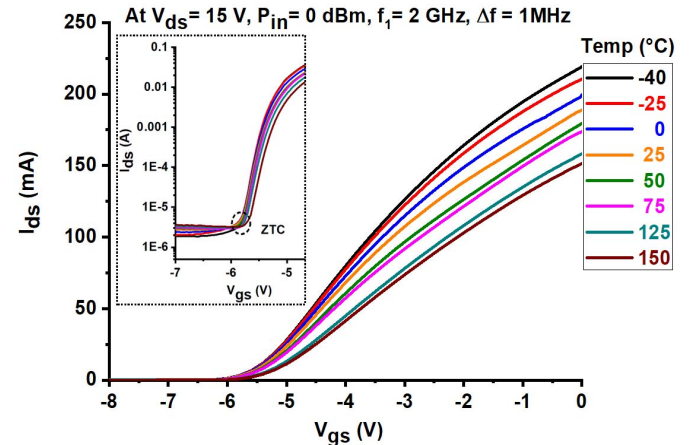


Fig. 4. Measured output current, I_{ds} of the GaN HEMT using two-tone setup (inset: the semi log transfer curve shows ZTC before threshold voltage).

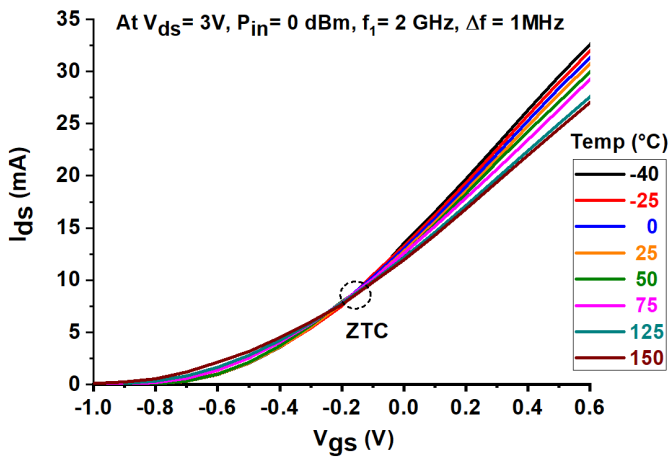


Fig. 5. Measured output current, I_{ds} of the GaAs HEMT using two-tone setup (inset: the semi log transfer curve shows ZTC after threshold voltage).

On the other hand, the magnitude of IMD3 increases up to 13.7 mA at -40°C and up to 12 mA at 150°C and after that decreased in GaAs HEMT. It can be seen that, the I_{ds} reduced up to the zero-temperature coefficient (ZTC) point in both cases after that increased with temperature which is clearly seen in the case of GaAs HEMT (see Fig. 5). The ZTC in the case of GaN HEMT is visible only in the semi-log plot of the transfer curve. The transfer curve in both cases reveals another important driving parameter of FET which is the threshold voltage, V_T . The V_T voltage varies from -5.7 V to -5.35 V at $V_{ds} = 15$ V in GaN HEMT while from -0.57 V to -0.69 V at $V_{ds} = 3$ V in GaAs HEMT when the temperature increases from -40°C up to 150°C . This data reveals that the V_T shifts positively in GaN HEMT and negatively in GaAs HEMT in response to temperature. It is seen that, the ZTC appears approximately at V_{gs} of -5.9 V which is before the threshold voltage measured in any temperature in the case of GaN HEMT (see Fig. 4). Meanwhile, the ZTC appears approximately at V_{gs} of -0.17 V which is actually after the threshold voltage V_T measured in any temperature in the case of GaAs HEMT (see Fig. 5). So, it can be concluded that, the ZTC is an indicator for the shifts of threshold voltage, V_T with temperature in GaN and GaAs HEMTs studied in this work.

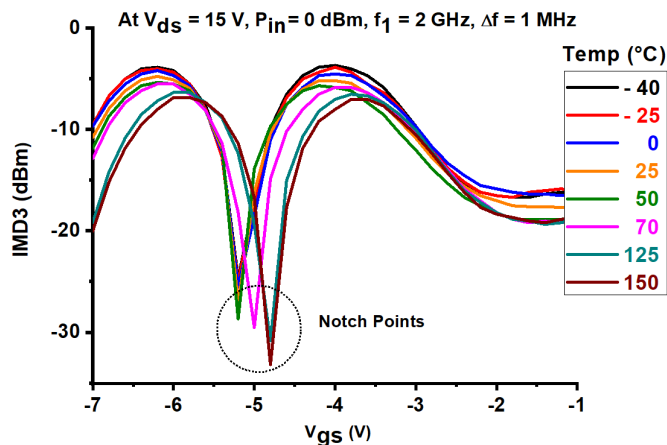


Fig. 6. Measured third-order intermodulation distortion (IMD3) product versus V_{gs} showing notches over temperature for the GaN HEMT.

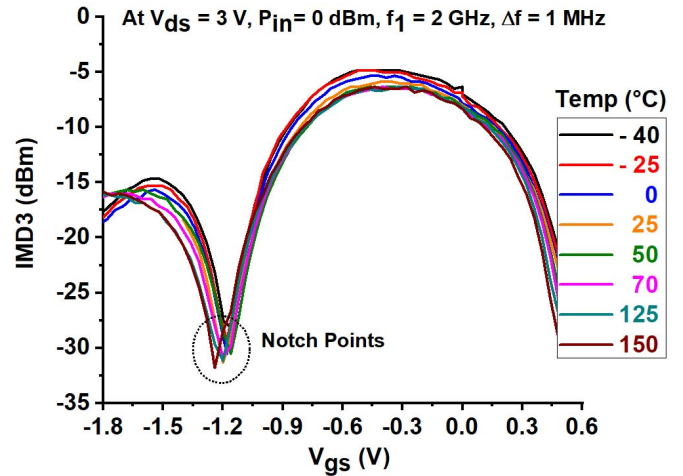


Fig. 7. Measured third-order intermodulation distortion (IMD3) product versus V_{gs} showing notches over temperature for the GaAs HEMT.

It is already reported that, the ZTC arises at a gate voltage, V_{gs} where a device exhibits constant DC performance with the variation of temperature. At the ZTC points ($\approx V_{gs}$), the degradation in V_T is counter-balanced by the declination of mobility [10]. In order to observe the shifts of notch point (i.e., at the V_{gs} trace where the notch appears) the third-order intermodulation distortion (IMD3) product against V_{gs} are presented in Figs. 6 and 7. The notch voltage, V_{notch} shifts from V_{gs} of -5.21 V to -4.78 V in GaN HEMT which is positively shifting with temperature. On the other hand, the notch voltage shifts from V_{gs} of -1.15 V to -1.25 V in GaAs based HEMT which is shifting negatively with temperature. These results affirm that, the notch voltage V_{notch} shifts exactly following the behaviour of threshold voltage V_T with temperature. The notch voltage V_{notch} , threshold voltage V_T along with the V_{pf} (i.e., the value of V_{gs} where the peak of transconductance g_m starts to fall) shifts with temperature for GaN and GaAs HEMTs with temperature is presented in Figs. 8 and 9. It can be seen that, all three parameters (V_{notch} , V_T and V_{pf}) increased with temperature wherein GaN HEMT and decreased with temperature wherein GaAs HEMT e.g., the trends are entirely opposing.

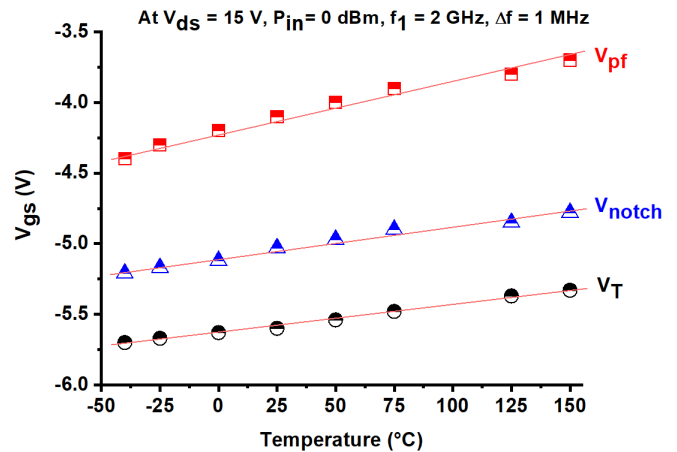


Fig. 8. The variation of V_{notch} , V_T and V_{pf} in GaN HEMT with temperature.

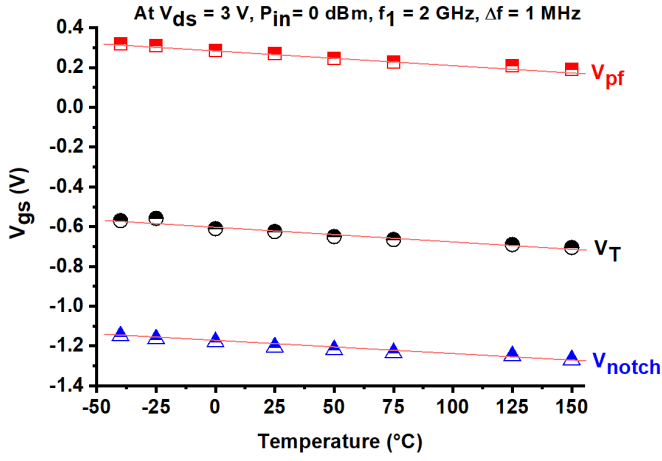


Fig. 9. The variation of V_{notch} , V_T and V_{pf} in GaAs HEMT with temperature.

Moreover, the notch point in IMD3 is raised in between the V_T and V_{pf} in GaN HEMT while before V_T and V_{pf} in GaAs HEMT (see Figs. 8 and 9). However, this phenomenon may vary from sample to sample and types of material used in device fabrication. The notch parameters proclaim an almost linear rise in GaN HEMT and fall in GaAs HEMT with the raising in temperature. Hence, the thermal coefficients (TCs) of the notch related parameters can be determined by using the relation: $(\Delta P_{\text{notch}}/P_0)/\Delta T$ where P_0 is notch parameter value measured at 25°C. The calculated TCs of V_T , V_{pf} , and V_{notch} are found to be about 0.035%/°C, 0.089%/°C, and 0.045%/°C, respectively for the GaN HEMT while -0.113%/°C, -0.214%/°C, and -0.052%/°C, respectively for GaAs HEMT. All these notch related parameters are clearly drain-source voltage dependent and the notch voltage V_{notch} exhibits less temperature-dependent.

B. Comparison between the measured and simulated notch current for GaN and GaAs HEMTs

Lastly, for the completeness of the study, it is necessary to compare the measured and simulated notch current for GaN and GaAs HEMTs. Table I represents the third order notch related parameters such as the notch voltage V_{notch} , threshold voltage V_T , the voltage at which the peak of transconductance g_m starts to fall, V_{pf} along with the values of g_{m3} for the studied GaN and GaAs HEMTs with temperature. Using these data in Table I, the simulated results for $I_{\text{ds_notch_IMD}_3}$ shows a very good agreement with the measured results (see Fig. 10). The data presented in Table I is at -40°C and 150°C only while all the data are used for simulation.

Table I. Third order notch related parameters with temperature.

Parameters	Variation in notch related parameters	
	GaN HEMT	GaAs HEMT
Temp (°C)	-40 to 150	-40 to 150
V_{notch} (V)	-5.21 to -4.78	-1.15 to -1.25
V_T (V)	-5.7 to -5.35	-0.57 to -0.69
V_{pf} (V)	-4.4 to -3.7	0.32 to 0.19
g_{m3} (mS/V ²)	0.88 to 0.45	0.029 to 0.022

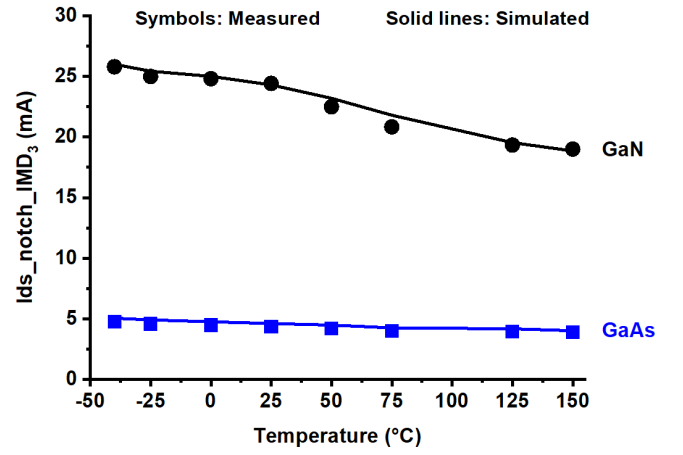


Fig. 10. The variation of V_{notch} , V_T and V_{pf} in GaAs HEMT with temperature.

IV. CONCLUSION

We have investigated the third-order notch for GaN and GaAs FETs over multi-bias and temperature by means of two-tone intermodulation distortion measurement. Three notch related parameters which arise at different V_{gs} trace are also investigated. The main findings are the degradation of notch current in GaN and GaAs FETs which follows the behaviour of output current with temperature. The notch voltage and the at which the peak of transconductance starts to fall exactly follow the trend of threshold voltage with temperature. The positive and negative shifting of notch related parameters in GaN and GaAs FETs represents some substantial perception for future design and optimizations.

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