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# Analysis of GaN-HEMT Switching Characteristics for High-Power Applications

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## Abstract

**We have newly developed the compact model HiSIM-GaN by solving the Poisson equation including the carrier trapping explicitly. Switching characteristics of Gallium Nitride (GaN) HEMT power devices has been analyzed based on measurements and simulation with the developed model. It is demonstrated that measured switching waveforms can be well reproduced by assuming that only one half of the DC-extracted trap density becomes electrically active during switching. This confirms that the trapping event requires time to accomplish. Additionally, it is also demonstrated that a field plate, introduced to relax the electric-field enhancement in the 2-dimensional electron gas (2DEG) of the channel region, has indeed a positive effect on circuit performances.**

## 1. Introduction

Power semiconductor devices based on different materials are used for various inverter and converter circuits in high power applications. Among them GaN-HEMT is considered to be very attractive due to its simultaneous applicability for both high power and high speed. The device has also been already successfully utilized for blue light emitting diode applications. The GaN material is generally considered to be superior to Silicon for realizing lower power loss in certain application ranges. However, non-negligible trap effects are a major concern for fully utilizing the advantageous GaN-material features.

In order to accurately predict power efficiency for enabling circuit-structure optimization, accurate compact modeling of dynamic device characteristics is a key [1, 2]. Therefore, we have developed HiSIM-GaN on the basis of a consistent solution of the Poisson equation. The model includes structural feature of GaN-HEMT devices such as field plates and the 2DEG existence. Our modeling and analysis focus is given on the influence of non-negligible trap states on circuit performances including the field-plate effects. A GaN-based boost converter circuit is analyzed in the investigation.

## 2. HiSIM-GaN Compact Modeling Approach

HiSIM (Hiroshima-university STARC IGFET Model) is the first complete surface-potential-based compact MOSFET model for circuit simulation based on a consistent solution of the Poisson equation. This concept has been extended to develop HiSIM-GaN by considering the potential distribution from the gate electrode to the substrate for precise modeling of the 2DEG features. The trap density is also considered in a self-consistent way. The field-plate is acting as a source of additional induced charge. All other possible phenomena expected for high voltage applications such as resistance and self-heating effects have been included in the same way as in HiSIM_HV, an industry-standard compact model for power devices [3].

## 3. Model Evaluation and Discussion

Fig. 1 shows a schematic of the studied GaN-HEMT. The device has a MIS structure with a SiN layer between the AlGaN layer and the gate electrode. In order to relax the electric field in the 2DEG region at the AlGaN / GaN interface, a structure with dual field plates at the gate and the source electrodes has been developed [4]. In order to investigate GaN-HEMT based circuits by simulation with HiSIM-GaN, we have first extracted the model parameters. Figs. 2 and 3 show the results for reproduction of measured current-voltage characteristics after parameter extraction using HiSIM-GaN. The DC trap density is extracted from the measured $I_{ds}$-$V_{gs}$ characteristics. The obtained trap density is more than ten times larger than for Silicon power devices. Fig. 4 shows measured and simulated capacitance characteristics. The capacitance results without the field-plate contributions are depicted together in Fig. 4 as horizontal dashed lines. As can be seen, all measured device characteristics, including the two stage capacitance characteristics, are well reproduced by HiSIM-GaN.

Switching characteristics are analyzed with the circuit of Fig. 5. In Fig. 6 the measured switching waveforms of the studied circuit are shown. Fig. 7 depicts the simulation results. Since the measurements include additional parasitic effects in the circuit as depicted in Fig. 5, all these parasitic values were separately extracted and included in the simulation as well. Fig. 7(a) shows the simulation results including the trap density extracted from the DC measurements. The current peaks induced during switch-on are clearly smaller than in the measurements. This is because of the large DC-trap density which results in a suppressed internal potential-reaction speed to the external bias changes. Fig. 7(b) shows the simulation results with a trap density of one half of the extracted DC value, which reproduces the measurements. This result suggests that the dynamically active trap density is different from the active trap density under the DC condition, and the transient waveform is required to extract the time constant of the trap event.

To confirm the influence of the field plate, besides the observed capacitance increase in Fig.4, we performed a turn-on circuit simulation for the GaN-HEMT device without field plate. An increase of the ringing is verified in Fig. 7(c). Thus it can be concluded that the field plate contributes not only to the reduction of the field peak but also increases the circuit stability. Additionally, a reduction of the circuit efficiency from 86.4% to 86.2% by neglecting the field plate is confirmed.

## 4. Conclusions

We have investigated the switching performance of GaN-HEMT devices with HiSIM-GaN, newly developed based on the Poisson equation including trap density and all other charges induced within the device. It is demonstrated that the extraction of the non-negligible trap density cannot be done only with DC measurements. Additionally, the relevant trap time constant has to be extracted from the transient GaN-HEMT switching characteristics. The field plate is shown to realize enhanced circuit stability and also enhanced circuit efficiency. Thus total device and circuit optimization is important to achieve the desired circuit performances.

## References


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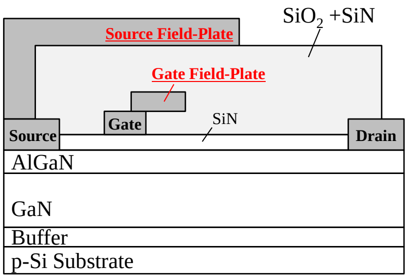


Fig. 1. Cross-sectional schematic of a GaN-HEMT device with dual field-plate technique [4].

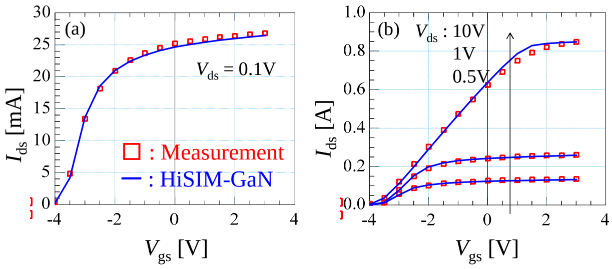


Fig. 2. $I_{ds}$-$V_{gs}$ characteristics at room temperature (a) $V_{ds}$=0.1V, (b) $V_{ds}$=0.5V, 1V, 10V. Symbols are measurements and lines are HiSIM-GaN results.

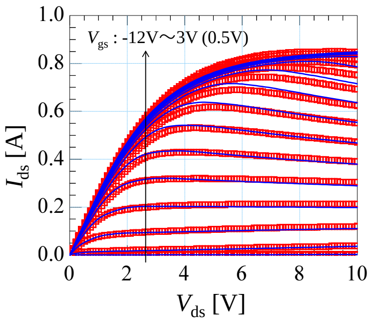


Fig. 3. $I_{ds}$-$V_{ds}$ characteristics at room temperature from $V_{gs}$=-12V to $V_{gs}$=3V. Symbols are measurements and lines are HiSIM-GaN results.

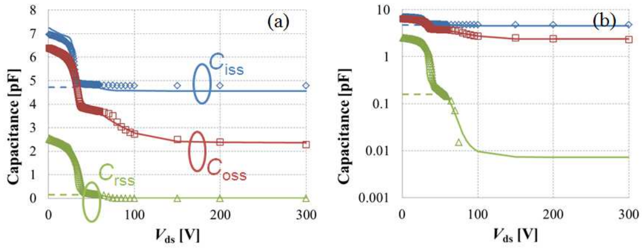


Fig. 4. Comparison of the modeled $C_{iss}$/$C_{oss}$/$C_{rss}$-$V_{ds}$ with measurements (a) Linear scale and (b) Log scale at room temperature with fixed $V_{gs}$ of -15V. Symbols are measurements and lines are HiSIM-GaN results. Dashed lines are HiSIM-GaN results without field plate.

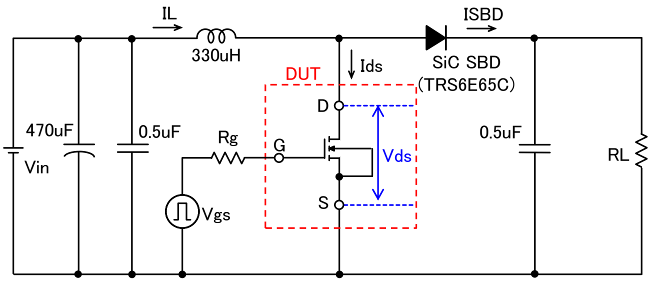


Fig. 5. Studied circuit diagram of the GaN-HEMPT-based boost converter circuit. The measurement conditions are input voltage of $V_{in}$=50V, switching frequency of $f_{sw}$=1MHz, and duty ratio=50%.

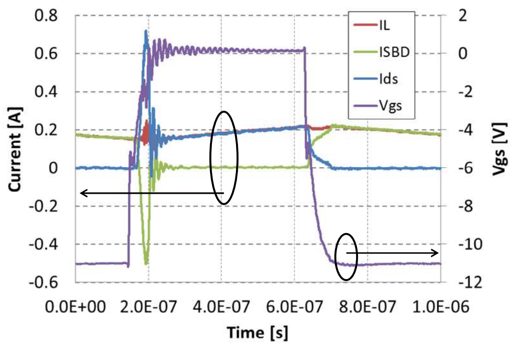


Fig. 6. Measured switching waveforms of the GaN-HEMT-based boost converter circuit (see Fig. 5). The gate resistance $R_g$=110 Ω and the load resistance $R_L$=1120 Ω are applied.

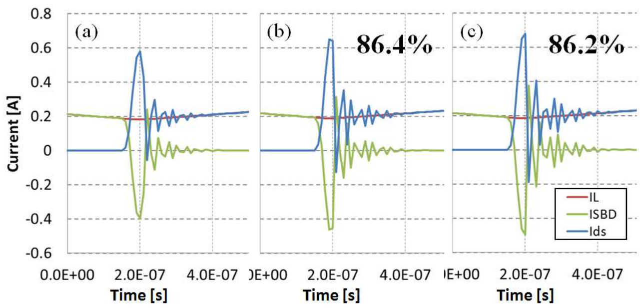


Fig. 7. Simulated turn-on current waveforms of the measured circuit (see Fig. 6). (a) With the trap density extracted from measured $I_{ds}$-$V_{gs}$ characteristics, (b) with one half of the extracted DC-trap density, (c) with the same trap density as the case (b) but without the field-plate effects. The circuit efficiency for the case (b) with the field plate is 86.4%, but it decreases to 86.2% by neglecting the field plate. The difference is small for the studied case due to the studied bias condition.