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Frequency-dependent C-V Based Extraction of Interface Trap Density in Normally-off Gate-recessed AlGaN/GaN Field-effect Transistors

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Abstract

The exact extraction of interface trap density (D_{it}) is very important especially in the gate-recessed MOS structure which is a promising approach for normally-off AlGaN/GaN field-effect transistors (FETs). In addition, the efficient C-V model should be precisely established including the frequency-dependence in AlGaN/GaN FETs because they are developed mainly for high speed applications. Here, the extraction of D_{it} is demonstrated in the normally-off gate-recessed AlGaN/GaN FETs and its result is compared with that of a conventional conductance method. The proposed method is not only simpler than the conductance method along with the same precision but also useful in a simple C-V model for AlGaN/GaN FETs.

Keywords: Normally-off, gate-recessed, AlGaN/GaN FETs, interface trap density, frequency-dependent C-V

1. Introduction

GaN-based high electron mobility transistors (HEMTs) have been attractive candidates for high power, high frequency application under high temperature due to its beneficial features, such as maximum frequency of oscillations, low specific on-resistance, and high breakdown voltage. It should be also noticed that the normally-off operation of GaN-based devices is important for commercializing the CMOS circuit-based applications [1]. The gate-recessed metal-oxide-semiconductor (MOS) structured AlGaN/GaN field-effect transistors (FETs) is a promising candidate for the normally-off GaN-based HEMT with advantages such as a thin barrier layer, low gate leakage, low gate swing, low turn on voltage and high break down voltage [2]. However, the interface trap density (D_{it}) should be exactly characterized especially in the gate-recessed AlGaN/GaN FETs because they would undergo the etching damage-induced trap generation in each interfacial layer, which would evoke the degradation of device performance as well as serious instability.

In this work, we demonstrate the D_{it} extraction by using the frequency-dependence of capacitance-voltage (*C-V*) characteristics in the gate-recessed normally-off AlGaN/GaN FETs. The proposed frequency-dependent *C-V* method (FDCM) is very useful in an efficient *C-V* model for AlGaN/GaN FETs because it supplies the frequency-independent bias-dependent capacitance components while the extracted D_{it} is consistent with that extracted from a conventional conductance method (CM) [3].

2. Result and Discussion

The used normally-off gate-recessed AlGaN/GaN FETs were integrated on a Si substrate as shown in Fig. 1(a). Fig. 1(b) shows the measured frequency-dependent *C-V* curve which was characterized through a typical *LCR* meter.

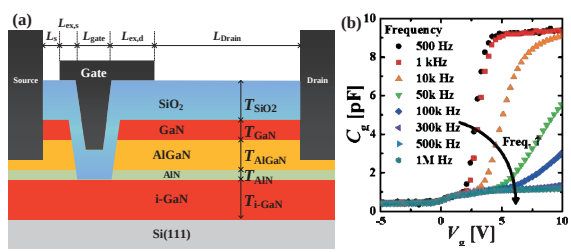

Fig. 1. (a) A schematic view of the normally-off gate-recessed AlGaN/GaN FETs. Geometrical parameters are W=100 μm, L_s=2 μm, $L_{ex,s}$=1 μm, L_{gate}=2 μm, $L_{ex,d}$=3 μm, L_{Drain}=12 μm, T_{SiO2}= 30 nm, T_{GaN}=4 nm, T_{AlGaN}=20 nm, T_{AlN}= 2 nm, and $T_{i\text{-}GaN}$=1.7 μm. (b) The measured C_g-V_g curve with various small-signal frequencies.

The result was derived from the observation through frequency dependence of capture-emission events caused by the interface and/or bulk traps as well as parasitic source/drain resistance (R_s). The model and physical assumption is similar to [4]. Both the parallel

mode capacitance (C_p) and the resistance (R_p) can be measured as a function of the gate voltage (V_g) under various frequencies as shown in Fig. 2(a). Then, the C_{ox} and R_s can be de-embedded in the four-element model in Fig. 2(b). The Z_M in the two-element model and Z_p in the four-element model are individually obtained by

$$Z_M = \frac{R_M}{1+(\omega C_M R_M)^2} - \frac{j\omega C_M R_M^2}{1+(\omega C_M R_M)^2} \quad (1)$$

$$Z_p = R_S + \frac{R_P}{1+(\omega C_p R_p)^2} - j\left(\frac{\omega C_p R_p^2}{1+(C_p R_p)^2} + \frac{1}{\omega C_{ox}}\right) \quad (2)$$

In addition, the R_s can be determined from the measured accumulation impedance at high frequency (f=1 MHz in our case) [3]:

$$R_s = \frac{R_{M,a}}{1+(\omega_{high} R_{M,a} C_{M,a})^2} \quad (3)$$

Thus, we can obtain the R_p and C_P as functions of experimentally acquired C_M and R_M by using Z_M=Z_p.

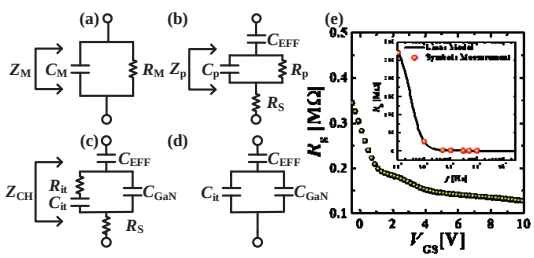

Fig. 2. (a) Equivalent circuit for the parallel mode impedance analyzer, (b) four-element model for the effective capacitance (C_{EFF}) and series resistance (R_s), (c) physics-based five-element model for frequency-dispersive *C-V* characteristics, (d) equivalent model for *f*-independent C_{EFF}, C_{GaN}, C_{it}, and (e) the R_s versus V_{GS} curve with the inset figure of the R_s versus frequency.

The following is the four-element model, which is transformed into the five-element model reflected in the interface trap model as shown in Fig. 2(c). The channel impedance Z_{CH} is composed of R_{it}, C_{it}, and C_{GaN}. By using Z_{CH}=Z_p, R_{it} is obtained as follows.

$$R_{it}^{\ 2} = \left\{ \frac{\omega^2 C_p R_p^{\ 2}\left(C_{it}+C_{GaN}\right)\left(C_{it}+C_{GaN}-C_p\right)}{\omega^2 C_{it}^{\ 2} C_{GaN}\left[1+\omega^2 C_p R_p^{\ 2}\left(C_p - C_{GaN}\right)\right]} - \frac{\left(C_{it}+C_{GaN}\right)}{\omega^2 C_{it}^{\ 2} C_{GaN}\left[1+\omega^2 C_p R_p^{\ 2}\left(C_p - C_{GaN}\right)\right]} \right\} \quad (4)$$

Then, using the relation of $R_{it}(\omega_1)$= $R_{it}(\omega_2)$=$R_{it}(\omega_3)$, we can obtain the C_{EFF}, C_{it}, and C_{GaN} as well as the *f*-independent C_g [Fig. 3(a)]. Finally, the D_{it} can be finally extracted by $C_{it}(V_g)$= $q^2 \times D_{it}(V_g) \times WL$ as shown in Fig. 3(b). Here, the $D_{it}(V_g)$ was transformed into $D_{it}(E)$ by using the *f*-independent C_g. The FDCM-based $D_{it}(E)$ was verified to be consistent with the CM-based $D_{it}(E)$ [Fig. 3(b)]. Furthermore, the FDCM is much simpler than CM because the former requires only three different *f* conditions while the latter many different *f* conditions.

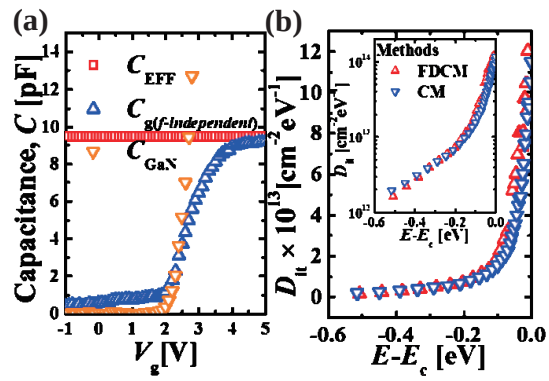

Fig. 3. (a) The extracted $C_{g(f\text{-independent})}$, C_{EFF}, and C_{GaN}. (b) The extracted $D_{it}(E)$ with the inset of semi-log plot.

3. Conclusion

The $D_{it}(E)$ of normally-off gate-recessed AlGaN/GaN FETs was successfully extracted by using FDCM. The proposed method is not only more efficient than a conventional CM along with the same precision but also very useful in a simple *C-V* model for AlGaN/GaN FETs.

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References

[1] T. Palacios, *et al.*, "High-power AlGaN/GaN HEMTs for Ka-band applications," *IEEE Electron Device Lett.*, **26**, pp. 781–783, November 2005.
[2] J. Shi, *et al.*, "High performance AlGaN/GaN power switch with HfO_2 insulation," *Appl. Phys. Lett.*, **95**, p. 042103, July 2009.
[3] E. H. Nicollian and J. R. Brews, *MOS(Metal Oxide Semiconductor) Physics and Technology*, Wiley, 2003.
[4] S. Lee, *et al.*," Extraction of Subgap Density of States in Amorphous InGaZnO Thin-Film Transistors by Using Multifrequency Capacitance–Voltage Characteristics", *IEEE electron Device Lett.*, 31, pp. 231-233, March 2010.