Trapping Phenomena in GaN HEMTs with Fe- and C-doped Buffer

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Abstract

GaN-based high electron mobility transistors (HEMTs) are a promising technology for high-frequency and high-power applications due to their high breakdown strength, superior electron transport characteristics, and their ability to support a large polarization-induced electron concentration. However, reliability issues in GaN HEMTs, such as trap-induced degradation, have drawn considerable attention in both academia and industry. Studies have been carried out on reducing the effect of traps via the optimization of the epitaxial structure of the HEMT. In this work, we focus on extracting and further analyzing the properties of traps in an AlGaN/GaN HEMT, shown in Fig. 1, with a doped GaN buffer. This device is fabricated and characterized at Mitsubishi Electric Corporation (Japan) and additional details regarding experimental methods will be presented elsewhere. The doping profile achieved during the epitaxial growth is shown in Fig. 2. Fe and C doping in the GaN buffer are typically employed to enhance the confinement of the two-dimensional electron gas (2DEG) in the channel and thus reduce buffer leakage [1]. The doping process also introduces traps in the buffer, which are found to be responsible for current collapse (CC) in GaN HEMTs. We analyze the trap characteristics in fabricated AlGaN/GaN HEMTs as a function of C doping in the buffer, while Fe doping concentration is fixed. The activation energy and cross section of traps in the fabricated devices are extracted from the Arrhenius plot of the drain current transient (DCT) measurements. Similar to previous works, we find that the C doping in GaN layer is mainly responsible for the acceptor-like trapping states with activation around 0.5 eV. We also conduct time-domain simulations of the HEMT using Sentaurus from Synopsys to understand the impact of trap characteristics on the transient response of this device. We conclude that for acceptor-like trapping states with large E A and small o, the current takes longer to recover from CC, while the trap concentration affects the degree of collapse.

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Introduction GaN-based high electron mobility transistors (HEMTs) are a promising technology for high-frequency and high-power applications due to their high breakdown strength, superior electron transport characteristics, and their ability to support a large polarization-induced electron concentration. However, reliability issues in GaN HEMTs, such as trap-induced degradation, have drawn considerable attention in both academia and industry. Studies have been carried out on reducing the effect of traps via the optimization of the epitaxial structure of the HEMT. In this work, we focus on extracting and further analyzing the properties of traps in an AlGaN/GaN HEMT, shown in Fig. 1, with a doped GaN buffer. This device is fabricated and characterized at Mitsubishi Electric Corporation (Japan) and additional details regarding experimental methods will be presented elsewhere. The doping profile achieved during the epitaxial growth is shown in Fig. 2. Fe and C doping in the GaN buffer are typically employed to enhance the confinement of the two-dimensional electron gas (2DEG) in the channel and thus reduce buffer leakage [1]. The doping process also introduces traps in the buffer, which are found to be responsible for current collapse (CC) in GaN HEMTs. We analyze the trap characteristics in fabricated AlGaN/GaN HEMTs as a function of C doping in the buffer, while Fe doping concentration is fixed. The activation energy (E_A) and cross section (σ) of traps in the fabricated devices are extracted from the Arrhenius plot of the drain current transient (DCT) measurements. Similar to previous works, we find that the C doping in GaN layer is mainly responsible for the acceptor-like trapping states with activation around 0.5 eV. We also conduct time-domain simulations of the HEMT using Sentaurus from Synopsys to understand the impact of trap characteristics on the transient response of this device. We conclude that for acceptor-like trapping states with large E_A and small σ, the current takes longer to recover from CC, while the trap concentration affects the degree of collapse.

Extraction and Analysis of Trap Characteristics The device under test (DUT) is first biased under the quiescent state (V_{dq} = 30 V, V_{gq} = -5 V) for 3 ms, then pulsed to the measurement state (V_d = 5 V, V_g = -1V). The drain current, I_d, is measured for various temperatures, ranging from -60°C to 30°C with ΔT = 10°C. Fig. 3 shows the measurement data at 30°C along with a polynomial fit to the data. The polynomial fit allows us to smooth out the noise in measurements and prepare the data for further analysis including taking its time derivative as shown in Fig. 4. The local extrema points in Fig. 4 correspond to the dominant trap-associated time constants (τ) in the device. Note that the maximum points suggest carrier emission process from the traps, while the minimum points suggest carrier capture process.

We extract τ from the DCT measurements at different temperatures to generate an Arrhenius plot as shown in Fig. 5. Noting that $\ln(\tau T^2) = \ln\left(\frac{h^3}{2(2\pi)^{3/2}\sqrt{3}m_e k^2 \sigma}\right) + \frac{E_A}{kT}$ (h is the Planck's constant, k is the Boltzmann constant, and $m_e = 0.22m_0$ is the effective mass of carriers), we extract E_A and σ values reported in Table 1.

The effect of traps on the transient response of the HEMT is further studied via TCAD simulations, wherein the doping and traps are introduced in the buffer and the channel region of the device. We assume that the traps are fully occupied at the quiescent state noted previously. Drift-diffusion simulation is adopted in TCAD in which the temperature is maintained at 300 K as the time duration of the voltage pulses during the transient operation is rather small to cause any appreciable self heating. Figs. 6 and 7 shows the effects of incorporating single trapping states with fixed concentration on transient response. In Fig. 8 we test the effects of trapping states concentration on transient response of the device, taking acceptor like traps with activation energy set to 0.5 eV, and cross section set to 1.7×10^{-12} cm^{-2}. This trapping state has been reported for heavily carbon-doped GaN. We choose the concentration of trapping states to be 10 times lower compared with the C doping concentration.

Conclusion The simulation results indicate that for acceptor(donor)-like trapping states with large (small) activation energy E_A and small cross section σ, the transient response takes longer delay to recover. While the concentration of the trapping states shows no impact on the response time, but the initial current level when pulsed signal applied.

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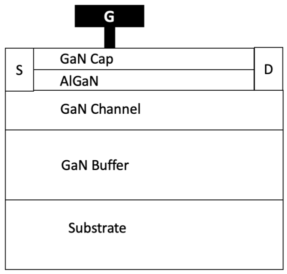

Fig. 1: Cross section of the GaN HEMT studied. The gate length is 400 nm with 1.25 μm gate-source and 3.75 μm gate-drain distance.

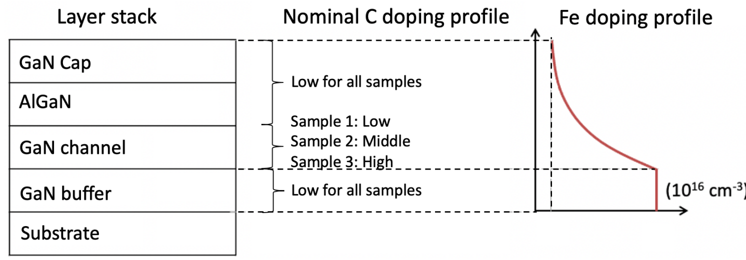

Fig. 2: Doping profile of iron and carbon in three different samples. The GaN buffer layer is uniformly doped with iron, while its doping concentration decays exponentially towards the top surface of GaN cap layer. Low Carbon doping concentration is applied across all epitaxial layers. While the carbon doping concentration in the channel layer is higher in sample 2 and 3.

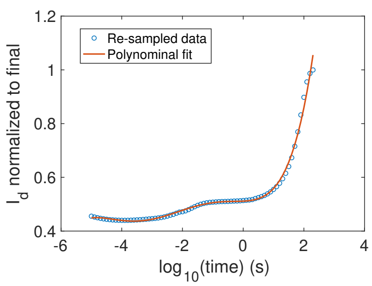

Fig. 3: Uniformly distributed data points (normalized transient response drain current) with respect to log_{10}(time). Solid line: Polynomial function with 8^{th} degree fitting to the data points.

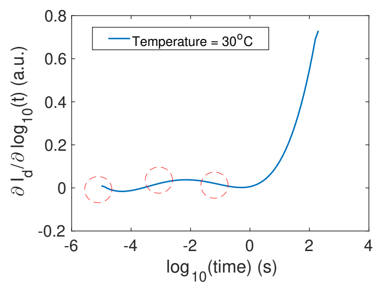

Fig. 4: Related differential of drain current transient response measured under 30^{o}C. Time corresponding to the maximum (minimum) points is the time constants of the emission (capturing) process.

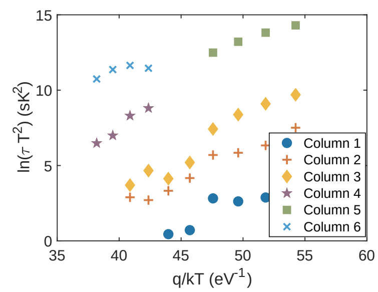

Fig. 5: Arrhenius plot based on time constants extracted under different temperatures. The column refers to Table 1, with E_A and σ extracted from the slope and y-axis intercept of linear fit to each branch of data.

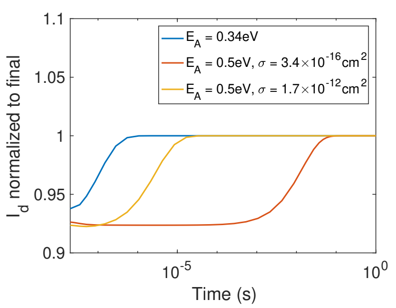

Fig. 6: Effects of single acceptor like trap states on device transient response.

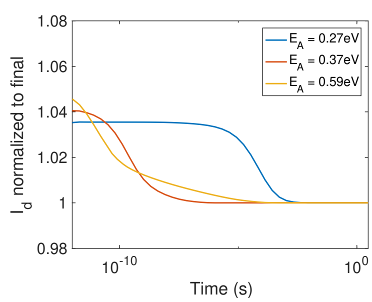

Fig. 7: Effects of single donor like trap states on device transient response.

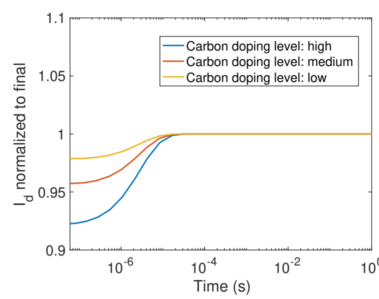

Fig. 8: Effects of trap states concentration on device transient response.

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
E_A (eV)	0.34	0.37	0.5	0.59	0.27	0.5
Cross section (σcm^2)	8.4×10^{-14}	3.0×10^{-14}	1.7×10^{-12}	6.2×10^{-13}	9.1×10^{-20}	3.4×10^{-16}
Type	Acceptor	Donor	Acceptor	Donor	Donor	Acceptor

Table 1: Identified activation energy and cross section based on Arrhenius plot.