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Electron traps studied in AlGaN/GaN HEMT on Si substrate using capacitance deep level transient spectroscopy

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Deep levels in AlGaN/GaN high electron mobility transistors (HEMTs) grown by molecular beam epitaxy on silicon (Si) substrates were characterized by the means Capacitance-Voltage and Deep Level Transient Spectroscopy. DLTS Measurements have revealed four electron traps with the binding energies of 0.08, 0.25, 0.47 and 0.59 eV and capture cross-sections of $2.02\text{x}10^{-18}$, $1.6\text{x}10^{-16}$, $1.2\text{x}10^{-12}$ and $7.02\text{x}10^{13}\text{cm}^{2}$ respectively. The concentrations of the traps were found at around of 10^{14}cm^{3}. The nature and the localization of the traps have been discussed.

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1. Introduction

Group III nitrides are attracting a great interest in semiconductor research, owing to their potential use in high-power microelectronic and optoelectronic devices. The binary nitrides of indium, gallium and aluminum as well as their ternary alloys have direct band gaps ranging from 1.9 to 6.2eV and, therefore, they are recommended for designing photodetectors, lasers and light emitting diodes operating in visible and ultraviolet spectral emission ranges. The specific properties of AlGaN such as wide band gap, thermal and radiation stabilites, chemical inertness, high breakdown voltage and high thermal conductivity are being utilized for the realization of microwave devices aimed to operate at high temperature and at high frequencies [1-5].

AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated a large potential for high frequency and high power applications. In addition to silicon, sapphire and silicon carbide which are commonly used as substrates, unfortunately, GaN has a high lattice mismatch to these substrates and so, it cannot be grown without a high concentration defects. However, the improvement of these performances is still subject to the influence of defects and traps which are responsible for anomalies in output characteristics I-V such as kink effect, current collapse, hysteresis phenomena and the shift of threshold voltage [6]. These anomalies are resulting from the presence of the trapping and detrapping mechanism of deep centers thermally activated in the transistor [7]. Thus, an understanding of defects and anomalies in these structures is essential for improving materials quality and consequently device performances. Many research experiences are directed toward understanding and eliminating these parasitic effects and minimizing the trapping effects [7-9].

In this work, Capacitance –Voltage and DLTS measurements have been performed on MBE grown AlGaN/GaN/Si HEMTs. The aim of the paper is to characterize the electron traps associated with deep-lying defects located at the surface and/or in bulk of the epitaxial layers. An attempt to explain the electrical behavior of the traps observed will be presented.

2. Experimental results and discussion

The structures to investigate consist of AlGaN/GaN HEMTs grown by MBE on resistive silicon (111) substrate (4000-10000Ω) using ammonia (Riber Compact 21). Details on the epitaxial growth are reported elsewhere[10] and layer thicknesses are taken as follows: a 50 nm AlN nucleation is at first grown on the Si (111) substrate followed by a 0.5 µm thick GaN/AlN sequence and a 30 nm thick undoped AlGaN layer grown on the 2µm GaN buffer and is capped with 1nm GaN. Deep-level transient spectroscopy has been used as a technique to characterize the electron traps in the AlGaN/GaN/Si heterostructures. Measurements were performed using double lock-in detection and a PAR410 capacitance meter and recorded in the temperature range 10-320K.

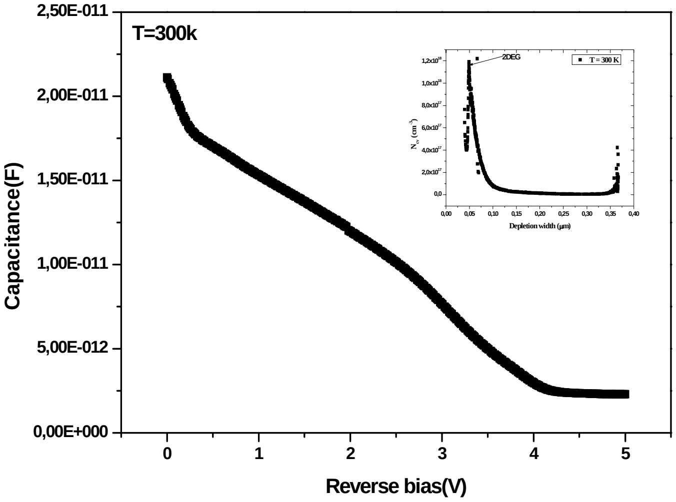

Fig. 1. Capacitance-Voltage measurements results obtained on AlGaN/GaN/Si HEMTs at T = 300K. In the inset, is reported the concentration N_{cv} versus the space charge width W.

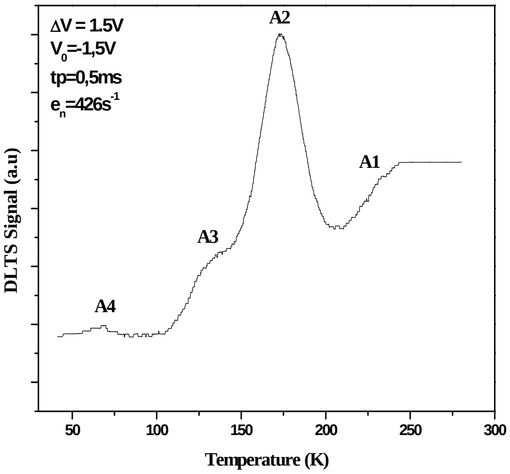

Fig. 2. DLTS spectra obtained on AlGaN/GaN/Si HEMTs.

The concentrations of deep traps are determined by Capacitance-Voltage measurements performed at room temperature on the AlGaN/GaN/Si HEMTs. Results are depicted in Fig.1. The inset shows the concentration $N_{C\text{-}V}$ versus the space charge layer width W as calculated from the equation:

$$N_{CV} = \frac{C^3}{q\,S^2\varepsilon(\frac{dC}{dV})} \qquad (1)$$

with $W = \frac{\varepsilon S}{C}$

where S denotes the Schottky barrier area, q is the elementary charge and ε is the dielectric constant. The carrier concentration profile is found to be 7.62x10^{17} cm^{-3}. Fig.2 shows the DLTS spectrum obtained for an emission rate e_n = 426 s^{-1}, a reversed bias V_0 = - 1.5V, a pulse amplitude ΔV = 1.5V and a filling time t_p = 0.5 ms. As seen, the spectrum indicates four electron traps labeled A1-A4. The ionization energies of these defects are evaluated from the signature, variation of the logarithm of $\frac{T^2}{e_n}$ versus temperature. The Arrhenius plots of the electron traps are shown in Fig.3. The physical parameters, obtained for the electron traps related to the DLTS peaks A1-A4 are summarized in table 1. The slope of an Arrhenius plot gives an apparent ionization energy, which shall be corrected by taking into account the dependence of the cross section on temperature in order to achieve the true energy level of the trap. Indeed, in the case of thermally activated capture cross section, i.e $\sigma = \sigma_0 \exp(\frac{-E_B}{K_B T})$, the apparent ionization energy E_i is the sum of the binding energy E_T and a capture barrier E_B such that $E_i = E_T + E_B$. We have measured the capture barrier using the method proposed by Criado et al [11]. According to this method, the barrier E_B can be deduced from the temperature-dependent DLTS spectrum amplitude ΔC_m, i.e from the slope of $Ln\left(-T^{-1/2}Ln(1-\frac{\Delta C_m}{\Delta C_0}\right)$ as a function of $\frac{1000}{T}$ where ΔC_0 is the peak amplitude corresponding to completely filled centers, Fig.4. The relevant values of the capture barriers as well as the apparent and real ionization energies are reported in table 2. In the following, we present the electrical characteristics of three electron traps A1-A3, we didn't determined the barrier defect A4 because his concentration is very low:

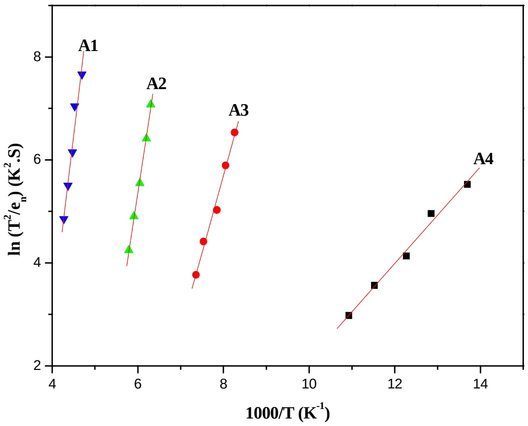

Fig. 3. Arrhenius plots of the electron traps observed in AlGaN/GaN/Si HEMTs.

Table 1. Physical parameters of the electron traps as deduced from the analysis of DLTS spectra.

Defects	ΔE_i(meV)	σ_n(cm^2)	N_T(cm^{-3})
A1	590	7.02x10^{-13}	3.03x10^{14}
A2	470	1.2x10^{-12}	2.18x10^{14}
A3	250	1.6x10^{-16}	5.9x10^{14}
A4	80	2.02x10^{-18}	8.83x10^{14}

Table 2. Barrier capture and apparent and real ionization energies of the electron traps

Defects	E_i(meV)	E_B(meV)	E_T(meV)
A1	590	40	550
A2	470	20	450
A3	250	10	240

The trap A1 is found to have an energy level at 590 meV, a capture cross section of 7.02×10^{-13} cm^2 and a concentration of 3.03×10^{14} cm^{-3}. The electron trap is similar to the trap reported by Yutaka Tokuda et al [12] using DLTS measurements on GaN layers grown by metal organic chemical-vapor deposition (MOCVD). It is also observed by Fang et al [13, 14] as well on n-GaN grown by MOCVD with DLTS measurements. The exact microscopic nature of this level is not established. It seems that this defect is located in the AlGaN layer.

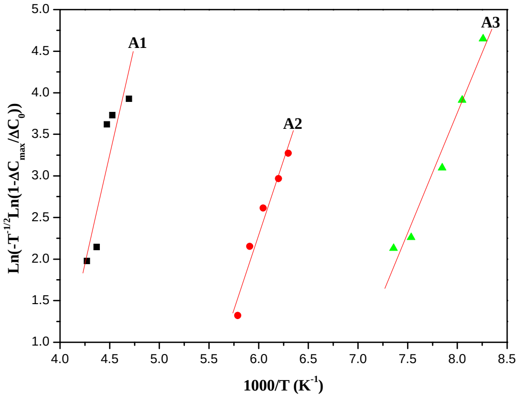

Fig. 4: Variation of the logarithm of $-T^{-1/2}Ln\left(1-\left(\frac{\Delta C_m}{\Delta C_0}\right)\right)$ *as a function of* $\frac{1000}{T}$.

The trap named A2 has an energy level at 470 meV, a capture cross section of 1.2×10^{-12} cm^2 and a concentration of 2.18×10^{14} cm^{-3}. This defect has been detected by Fang et al [15] using DLTS measurements on n-GaN grown by hydride vapor phase epitaxy. A comparison of the obtained activation energies with the ones reported in the literature the electron trap A2 to the so-called E2 center. This trap is most probably located in the region near the 2DEG.

The electron trap A3 is characterized by an activation energy 250 meV, a capture cross section of 1.6×10^{-16} cm^2 and a concentration of 5.9x10^{14} cm^{-3}. The defect has been detected by Gassoumi et al [16] using CDLTS on AlGaN/GaN HEMTs grown by MBE. This electron trap corresponds to that reported by Z.-Q.Fang [15]. This trap could be a complex involving V_{Ga} such as V_N-V_{Ga}. It could possibly be also a defect located at the AlGaN/GaN heterointerface.

The trap A4 has an activation energy of 80 meV, a capture cross section 2.02x10^{-18} cm^2 and a concentration of 8.83×10^{14} cm^{-3}. This defect is observed in the present study as well as in the work of Gassoumi et al [17] and not elsewhere. This electron trap has been identified as an N vacancy (V_N). It seems to be located near the gate of the HEMT AlGaN/GaN/Si.

While the exact origin of the four levels detected cannot to be certain and is still an open question, but we may affirm that for DLTS measurements, these traps are all located under the gate in the AlGaN top layer and/or near 2DEG and/or at the surface.

3. Summary

We have investigated AlGaN/GaN/Si HEMTs grown by MBE by using DLTS technique. Results reveal the presence of four electron traps A1, A2, A3 and A4 located at 0.59, 0.47, 0.25 and 0.08 eV with respect to the bottom of the conduction-band in the AlGaN barrier. The traps A1, A2 and A3 were identified. As for the electron trap A4, it has not been frequently observed in HEMTs based on AlGaN/GaN. The origin of this center is not clear. The characterization of defects is of main interest for the future development of high power RF transistors based on group-III nitrides. Adding a passivating layer in AlGaN/GaN HEMTs would be a key issue towards this end.

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