Influence of surface states on deep level transient spectroscopy in AlGaN/GaN heterostructure*

Qing Zhu(朱青)[1,2], Xiao-Hua Ma(马晓华)[1,2,†], Wei-Wei Chen(陈伟伟)[1,2], Bin Hou(侯斌)[1,2], Jie-Jie Zhu(祝杰杰)[1,2], Meng Zhang(张濛)[1,2], Li-Xiang Chen(陈丽香)[1,2], Yan-Rong Cao(曹艳荣)[3], and Yue Hao(郝跃)[2]

[1] *School of Advanced Materials and Nanotechnology, Xidian University, Xi'an* 710071, *China*
[2] *Key Laboratory of Wide Band-Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an* 710071, *China*
[3] *School of Mechano-electric Engineering, Xidian University, Xi'an* 710071, *China*

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Deep level transient spectroscopy (DLTS) as a method to investigate deep traps in AlGaN/GaN heterostructure or high electron mobility transistors (HEMTs) has been widely utilized. The DLTS measurements under different bias conditions are carried out in this paper. Two hole-like traps with active energies of $E_v + 0.47$ eV, and $E_v + 0.10$ eV are observed, which are related to surface states. The electron traps with active energies of $E_c - 0.56$ eV are located in the channel, those with $E_c - 0.33$ eV and $E_c - 0.88$ eV are located in the AlGaN layer. The presence of surface states has a strong influence on the detection of electron traps, especially when the electron traps are low in density. The DLTS signal peak height of the electron trap is reduced and even disappears due to the presence of plentiful surface state.

Keywords: AlGaN/GaN, hole-like traps, DLTS, surface states

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1. Introduction

Trapping effect in AlGaN/GaN high electron mobility transistors (HEMTs) presents a major limitation to the power performance at high frequencies and the dynamic performance, for the density of two-dimensional electron gas (2DEG) is changed by the electrical charge trapped in the bulk and on the surface.

Deep level transient spectroscopy (DLTS), as one rapid, sensitive, and straightforward technology, has been utilized in GaN-based devices since 1994.[1] Three main native traps have been introduced: 0.15 eV–0.26 eV (E1),[2–4] 0.5 eV–0.61 eV (E2),[4–6] and 0.67 eV–0.89 eV (E3),[6,7] which are related to nitrogen vacancy, nitrogen antisite and nitrogen interstitial, respectively. The traps with responding to dopants have been investigated by some groups. C doping will introduce a new trap with an energy of $E_c - 0.4$ eV (C_{Ga}) and reduce the concentration of N_{Ga}.[8] Fe doping in the GaN buffer layer can induce a strong current collapse and increase the concentration of trap with an energy of $E_c - 0.63$ eV, which does not relate to the iron atoms but more likely to an intrinsic trap.[9] Sasikumar *et al.*[10] reported that the $E_c - 0.45$ eV trap was the dominant electrical stress-affected trap and likely caused the HEMT drain-lag and increased the mild knee-walkout. Deep levels induced by electron irradiation[11] and proton irradiation[12] have been investigated. Bisi *et al.*[13] summarized more than 60 papers and made a database of the deep levels in GaN- and AlGaN- based layers and devices. The DLTS measurement becomes more difficult as the structure of GaN- based devices is more complex. Look and Fang[14] investigated the method to distinguish the trap on the surface from that in the bulk for the GaN bulk material. However, it is not easy to directly detect the surface traps in the complex structure such as AlGaN/GaN heterostructure, while the charging and discharging of surface state has an important effect on the density of 2DEG in the channel and the DLTS measurement of traps in the channel. Okino *et al.*[15] reported the surface-state-related DLTS signals in AlGaN/GaN HEMTs by I-DLTS.

In this study, DLTS measurements are applied to AlGaN/GaN heterostructure with various reverse voltages, filling pulse voltages and widths. Hole-like traps are detected and related to surface states that affect DLTS signals of other electron traps.

2. Devices and experiments

The AlGaN/GaN hetero-junction structure used in this paper was grown by metal-organic chemical vapour deposition (MOCVD) on a (0001) sapphire substrate. The epitaxial structure was composed of, from the substrate up, a nuclear layer, a 1.3-μm-thick unintentionally doped (UID) GaN layer, a 1-nm-thick AlN interlayer, and a 20-nm-thick unintentionally doped $Al_{0.3}Ga_{0.7}N$ barrier layer. Circular shaped Schottky diodes were utilized for CV, IV, and DLTS measurements, each with

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†Corresponding author. E-mail: xhma@xidian.edu.cn

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a circular gate contact having a diameter of 130 μm and surrounding ohmic contact with an Ohmic–Schottky separation of 30 μm (as shown in Fig. 1). Mesa isolation was performed by Cl_2-based reactive ion etching (RIE). Ohmic contact was realized by consecutively annealing the e-beam evaporated Ti/Al/Ni/Au (20 nm/140 nm/55 nm/45 nm) at 850 °C for 30 s in nitrogen ambient. It was followed by a 60-nm plasma-enhanced chemical vapour deposition (PECVD) Si_3N_4 passivation layer. The Si_3N_4 in the gate area was removed by RIE, and then the metal stacks of Ni/Au (45 nm/200 nm) were deposited to form the Schottky contact. Finally, Si_3N_4 (200-nm thick) as a second surface passivation film was deposited.

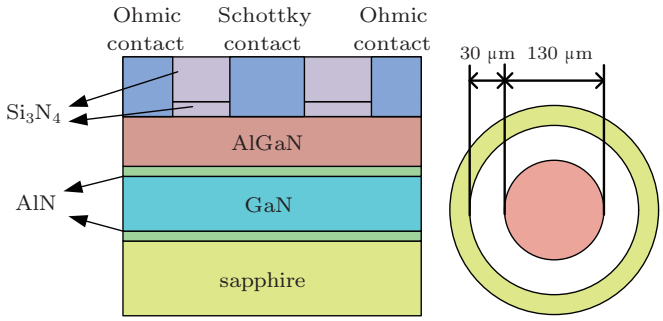


Fig. 1. (color online) Dimensional layout of fabricated Schottky diode incross-sectional (a) and top view (b).

The *C*–*V* and *I*–*V* characteristics were measured at room temperature in the dark to characterize the devices and determine the voltage range applied in the DLTS measurements using the Semetrol DLTS system. The frequency of *C*–*V* and DLTS measurement was 1 MHz. The temperature range was from 45 K to 450 K in DLTS measurement.

3. Results and discussion

The *I*–*V* and *C*–*V* characteristics are shown in Fig. 2. The values of forward and reverse current are small enough to meet the requirements of the Semetrol DLTS system.

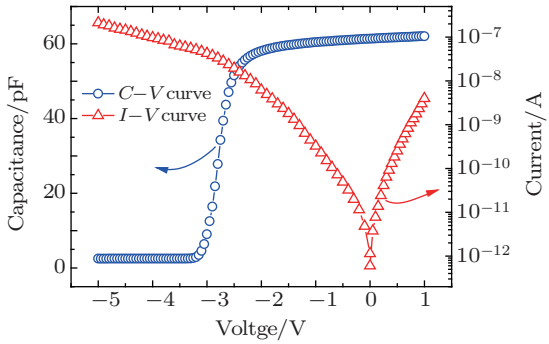


Fig. 2. (color online) *C*–*V* and *I*–*V* characteristics at room temperature in the dark.

The DLTS spectrum measured in the pinch-off region ($V_r = -3$ V, $V_f = -2$ V, pulse width = 0.1 ms) is shown in Fig. 3(a). The main capture and emission processes take place in the AlGaN/GaN interface under the present bias condition according to the CV curve in Fig. 2. One electron trap around 300K is detected and the trap energy is $E_c - 0.56$ eV and the capture cross section is 7×10^{-15} cm^{-2}, which is close to the reported result of the DLTS measurement in Ref. [16]. Three samples (AlGaN/GaN HEMT, InAlN/GaN HEMT and GaN bulk) were measured by multifarious methods to confirm the electron trap of 0.57 eV to be an intrinsic trap in GaN,[16] and the nature of this trap has been considered to be nitrogen antisites.[5,6]

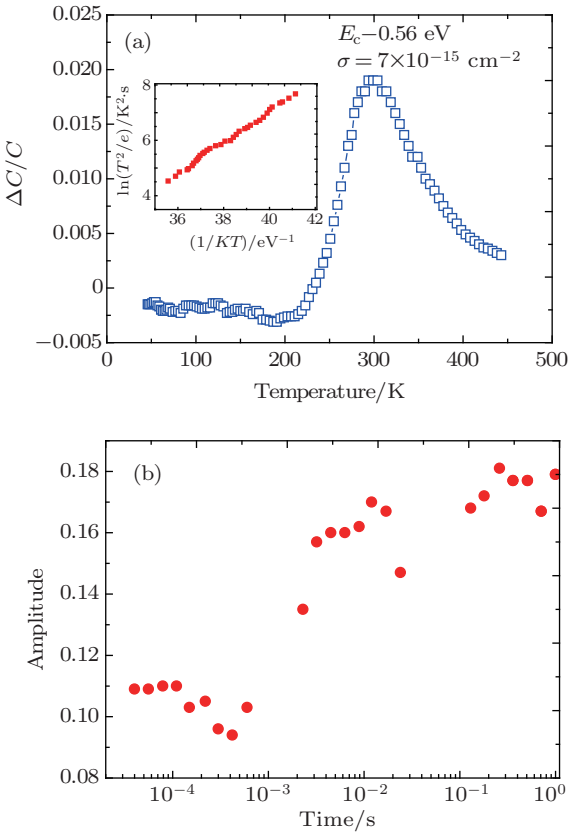


Fig. 3. (color online) (a) DLTS spectrum with a rate window $e = 133$ s^{-1} and Arrhenius plots (inset) with $V_r = -3$ V, $V_f = -2$ V, and pulse width = 0.1 ms. (b) Pulse width dependence of the transient capacitance amplitude at 300 K with $V_r = -3$ V and $V_f = -2$ V.

The pulse width dependence of the transient capacitance amplitude at 300 K is exhibited in Fig. 3(b). During the measurement, it is found that the amplitude related to a positive DLTS signal (electron trap or majority trap signal) decreases as the pulse width gradually increases until 0.4 ms, and the negative signal arises and the amplitude increases as the pulse width is larger than 0.4 ms, which may be caused by overlapping multiple traps. Partial charges are emitted from the trap with an active energy of $E_c - 0.56$ eV, as the filling width becomes larger than its typical emission time constant, which contributes to reducing the amplitude of the electron-trap signal.[13] The results can be confirmed in Fig. 4.

The DLTS scan with 50-ms filling pulse and the same voltage settings as those in Fig. 3 ($V_r = -3$ V, $V_f = -2$ V) shows obviously two negative peaks H_1 and H_2 corresponding to a trap energy of $E_v + 0.47$ eV, capture cross section of

1.2×10^{-14} cm^{-2} and $E_v + 0.10$ eV, capture cross section of 4.9×10^{-21} cm^{-2}, respectively. The negative peaks are not likely corresponding to the change in hole-trap state in the bulk, for the hole traps in the bulk are usually occupied by electrons and could not contribute to the capacitance transient. What is more, holes can hardly be generated in the bulk under the present bias condition.

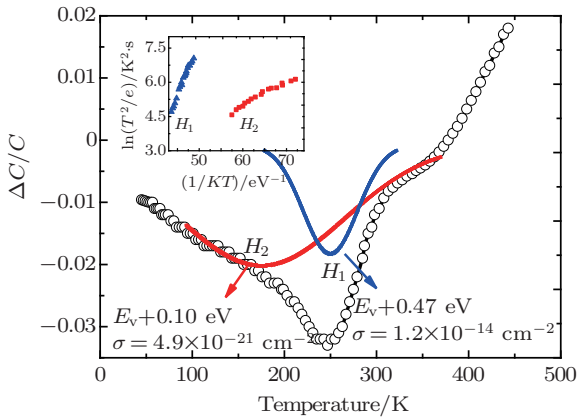


Fig. 4. (color online) DLTS spectra with a rate window $e = 133$ s^{-1} and Arrhenius plots (inset) with $V_r = -3$ V, $V_f = -2$ V, and pulse width = 50 ms.

Negatively going DLTS signals have been studied for GaAs metal-semiconductor field effect transistors and AlGaAs/GaAs HEMTs since 1986.[17–19] The hole-like trap signal can be explained by the variation in the population of surface states occupied by electrons. The Si_3N_4 layer directly passivates the deep donor state on the AlGaN surface, introduces large-density fast state traps,[20] and may be related to the incorporation of silicon atoms at the SiN/AlGaN interface,[21,22] which can explain the presence of H_1 in Fig. 4. The details in the formation of the hole-like trap signal will be discussed in this paper later.

Ibbetson *et al.*[23] and Smorchkova *et al.*[24] proposed that surface donor-like traps are the source of the electrons in the channel, and the electrons are driven into the channel by the strong polarization field. Surface states can capture electrons to form a "virtual gate" on the ungated surface.[25] The response of the depletion region under the "virtual gate" is much slower than that under the real gate contact.

The transient behavior of the depletion region under the gate and surface is illustrated schematically in Fig. 5. Electrons injected from the gate are captured by surface states and the depletion layer under ungated surface extends to a steady position just before the filling pulse at $t = t_1$ as shown in Fig. 5(a). The change in population of surface states, which are occupied by electrons before filling pulses, emit electrons during a filling pulse, and re-capture electrons after a filling pulse, results in a change in 2DEG density due to the charge neutrality, and consequently contributes to capacitance transient performance.

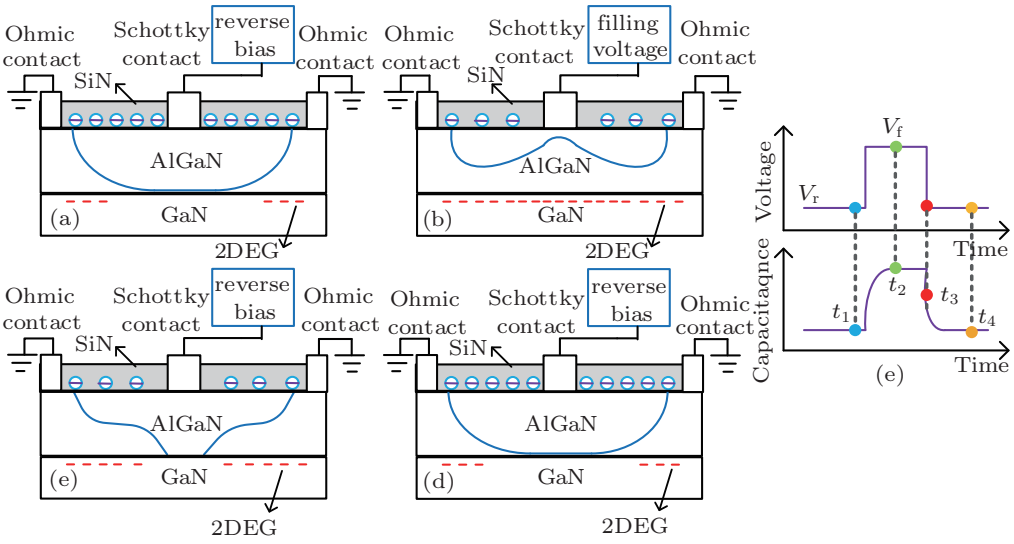


Fig. 5. (color online) Schematic illustrations of the response of the depletion layers: (a)–(d) the responses of the depletion layer at the times of t_1, t_2, t_3, and t_4, respectively, and (e) time dependences of voltage and capacitance.

When the gate switches to a filling pulse, gate depletion shrinks instantaneously, while the depletion region under an ungated surface cannot respond to gate voltage immediately, for it takes a longer time to emit electrons from the surface states as the process between t_1 and t_2 in Fig. 5(e). The number of electrons emitted from surface states depends on the amplitude and width of filling pulses. The density of 2DEG under the ungated surface increases and gradually becomes steady as the virtual gate effect weakens. As a result, the capacitance maintains a larger value until t_3.

When the filling pulse switches to reverse bias, the virtual gate effect becomes stronger again and the surface states restart to capture electrons. The relatively slow capture process gives rise to the decreasing of capacitance due to the reduced 2DEG between t_3 and t_4 as shown in Figs. 5(c) and 5(d), directly resulting in the formation of hole-like trap sig-

nals. The reason for the slow capture process is that it needs three steps: electron injection from the gate, electron transport on the surface and electron capture at surface states. This can explain the difference between Figs. 3(a) and 4, which show that electron trap spectra appear for short filling pulse width, on the contrary, the hole-like trap dominates for longer pulse width.

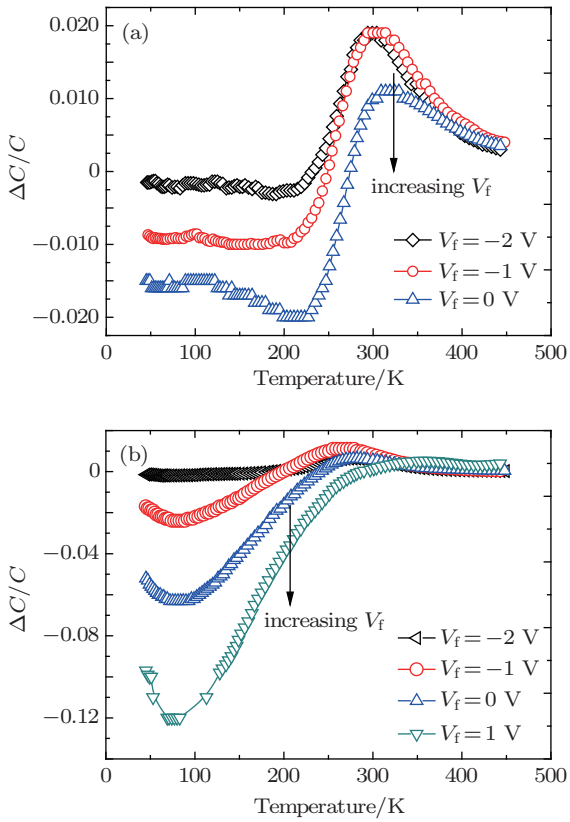


Fig. 6. (color online) DLTS spectra measured each as a function of filling pulse height with a rate window $e = 133\ s^{-1}$ when pulse width is 0.1 ms. (a) V_r is -3 V and (b) V_r is -2.7 V.

Figure 6 shows that the hole-like trap signal prefers to arise, with more positive filling pulses applied. More surface states occupied by electrons participate in the emitting process with the filling pulses increasing. Even though the filling pulse width is 0.1 ms and partial surface states may not reach the steady state, the signal of the hole-like trap can arise obviously when there are forward enough filling pulses applied, for the fast state traps on the surface introduced by the SiN passivation layer.

It seems that the concentration of hole-like traps in Fig. 6(b) is larger than that in Fig. 6(a). The dynamic process during the measurement is determined by the combined effect of electron traps in the bulk and on the surface. Less sampling volume is involved when the reverse voltage is -2.7 V than that with $V_r = -3$ V, and the corresponding electron traps in the bulk reduce, especially at the interface, which participate in the capturing and emitting process, resulting in the fact that hole-like traps are related to surface states in Fig. 6(b) hold more dominant position during the measurements than in Fig. 6(a). It suggests that surface states have a great influence on the detection of electron traps, especially when the electron traps are low in density.

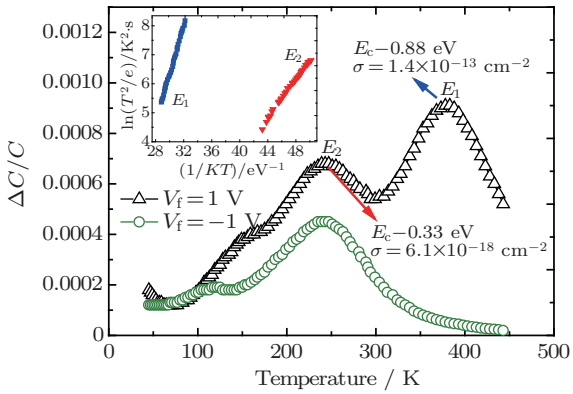


Fig. 7. (color online) DLTS spectra with a rate window $e = 133\ s^{-1}$ and Arrhenius plots (inset) as $V_r = -2$ V, pulse width = 0.1 ms.

Our measurements show that the negative signal does not appear when reverse voltage is -2 V and pulse width is 0.1 ms. E_1 ($E_c - 0.88$ eV, $\sigma = 1.4\times10^{-13}$ cm^{-2}) and E_2 ($E_c - 0.33$ eV, $\sigma = 6.1\times10^{-18}$ cm^{-2}) are detected and shown in Fig. 7. The traps are considered in the AlGaN barrier layer under this bias condition. The origin of E1 is supposed to be nitrogen antisites, the same as the trap in Fig. 3(a), because in $Al_xGa_{1-x}N$ material the activation energy becomes larger and the signal peak moves towards the high temperature direction for congener traps as the Al composition increases.[26–28] E_2 is supposed to be nitrogen vacancy which is not detected in Fig. 3(a) on account of the influence of surface states. As a result of the low reverse bias, the formation of a virtual gate is suppressed and the quantity of surface states participating in the dynamic process is very small, which has little influence on the detection of electron traps.

4. Conclusions

The DLTS measurements under different bias conditions are carried out in this paper. Hole–like traps are detected as a result of surface states emitting and re-capturing electrons. The DLTS signal peak height of the electron trap is reduced and even disappears with the advent of plentiful surface states. Suppression of surface states is very important for not only optimizing the performance of the device but also improving the veracity of electron trap DLTS measurements in AlGaN/GaN heterostructure. In addition, traps on the surface need to be further investigated in order to be controlled better.

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