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Ion-assisted gate recess process induced damage in GaN channel of AlGaN/GaN Schottky barrier diodes studied by deep level transient spectroscopy

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Deep traps in AlGaN/GaN Schottky barrier diodes have been investigated using deep level transient spectroscopy. It has been found that ion-assisted gate recess process leads to the formation of electron traps. The defects related to these traps are mainly located in the two-dimensional electron gas channel below the Schottky contact, meaning that the partial etching of the AlGaN layer produces damage on the top of the underlying GaN layer. The activation energies of the electron traps, extracted from the data, range between 0.28 and 0.41 eV. We believe that these centers are complexes linked with nitrogen vacancies which may behave as extended defects.

1. Introduction

Many high power transistors¹⁻⁶ or Schottky diodes^{7,8} use a recessed gate geometry in which the gate metals are deposited on an etched surface to position the gate slightly below the surface. The recessed gate structure is very attractive for fabricating normally off high-voltage AlGaN/GaN high-electron mobility transistors (HEMTs)⁹ because the gate threshold voltage can be controlled by the etching depth of the recess without significant increase in on-resistance characteristics.¹⁰ Normally off characteristics are strongly favored for power electronics applications to prevent device destruction due to the short circuit which occurs when the gate signal becomes ground voltage for normally-on devices.

Compared to wet chemical etching, ion-assisted etch processes offer the possibility of better control over the depth and profile of the recess. However, these processes introduce the possibility of damage to the transistor channel.¹¹ Reactive ion etching (RIE),¹² inductively coupled plasma (ICP)¹³ etching, and ICP-RIE¹⁴ of GaN have been shown to severely degrade the Schottky contact, decreasing the Schottky barrier height and increasing the reverse leakage current by several orders of magnitudes. By using deep level transient spectroscopy (DLTS), several traps have been found in unintentionally doped n-GaN samples grown by metal-organic chemical vapor deposition (MOCVD) and subjected to ICP-RIE, with Cl₂/Ar gas chemistry.¹⁵

The influence of dry-etching damage on the electrical properties of an AlGaN/GaN Schottky barrier diodes (SBD) with recessed anode has recently been reported.¹⁶ In this work, we used DLTS to demonstrate that the AlGaN etching induces electron traps in GaN channel of AlGaN/GaN SBD.

2. Experimental methods

The AlGaN/GaN bilayer was grown by MOCVD on a 200 mm diameter silicon substrate, oriented (111). The epitaxy consists of an AlN nucleation layer, followed by 1.6 μm of AlGaN buffer layers, then a 1.6 μm thick semi-insulating carbon doped GaN buffer layer, a 100 nm unintentionally doped GaN layer acting as the channel, a 1 nm unintentionally doped AlN layer and a 24 nm uninten-

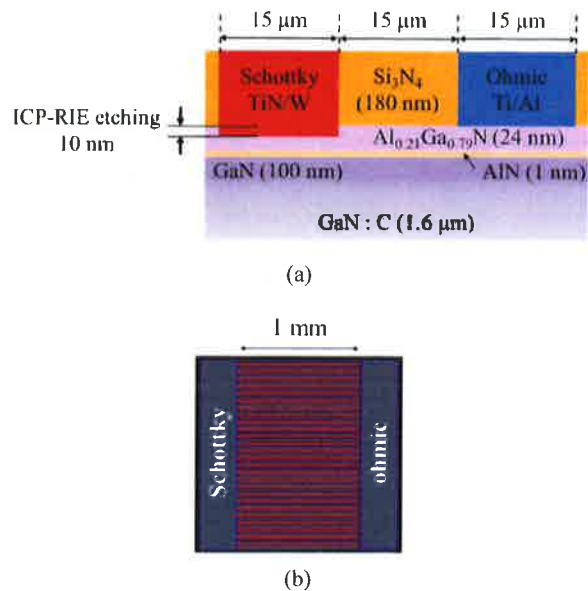


Fig. 1. (Color online) (a) AlGaN/GaN Schottky barrier diode schematic and (b) interdigitated comb-like structure with twenty six $15 \times 1000 \mu\text{m}^2$ fingers.

tionally doped Al_{0.21}Ga_{0.79}N barrier layer [Fig. 1(a)]. Interdigitated comb-like diodes with twenty six $15 \times 1000 \mu\text{m}^2$ fingers were then formed using TiN/W as Schottky electrodes and Ti/Al annealed for 30 s at 875 °C as ohmic contacts [Fig. 1(b)]. Recessed Schottky electrodes were achieved by etching 10 nm of the AlGaN layer using ICP-RIE, with BCl₃/Ar-He gas chemistry and 100 V DC bias. The Schottky/ohmic spacing is 15 μm and is passivated with Si₃N₄. The room temperature sheet carrier density was measured to be $n_{\text{sh}} = 4.13 \times 10^{12} \text{cm}^{-2}$. Data were acquired with a DLTS system using a Boonton 7200 capacitance meter with a 100 mV test signal at 1 MHz.

3. Results and discussion

DLTS measurements were carried out on diodes with and without a recessed gate. The spectra, reported in Fig. 2, were recorded with a reverse bias $V_R = -2 \text{ V}$, a filling pulse height

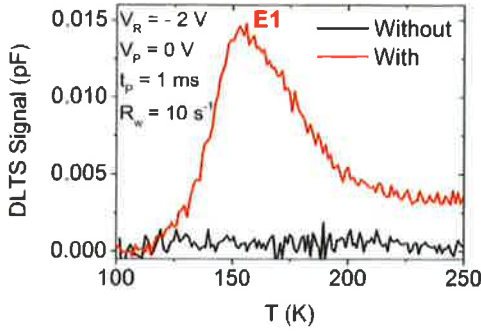


Fig. 2. (Color online) DLTS spectra of samples with and without a recessed gate. The asymmetrical peak around 150 K indicates the presence of defects in the GaN layer of the recessed gate SBD.

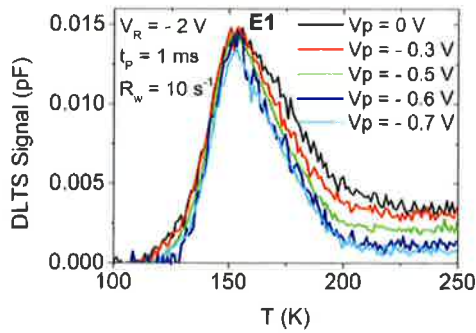


Fig. 3. (Color online) DLTS spectra of the recessed gate SBD for V_p varying from 0 to -0.7 V. The amplitude of the peak does not change when the filling pulse height is reduced.

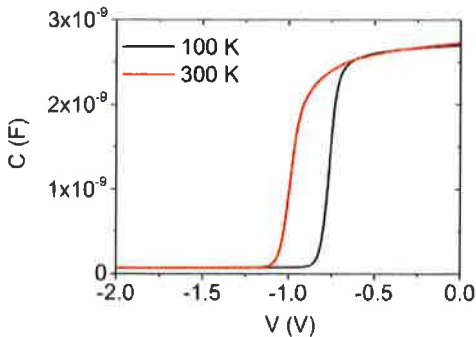


Fig. 4. (Color online) Capacitance versus voltage measurement of the recessed gate sample. The pinch-off of the SDB is -0.85 V at 100 K and -1.1 V at 300 K.

$V_p = 0$ V and a filling pulse width $t_p = 1$ ms. The SBD without AlGaIn etching step does not exhibit a DLTS signal in the temperature range 100–250 K. However, an asymmetrical peak around 150 K (labeled E1) appears on the DLTS spectrum of the SBD which has undergone the gate recess process. In Fig. 3, we see the modification of this peak as a function of the filling pulse height V_p . The pinch-off of the SBD, determined by capacitance voltage measurement, is -0.85 V at 100 K and -1.1 V at 300 K (Fig. 4). Consequently, by changing V_p between 0 and -0.7 V, the filling pulse height stays in a region where the channel remains open over the full range of temperature used during DLTS scans. For $V_p = 0$ V, the probe zone is close to the GaN surface and

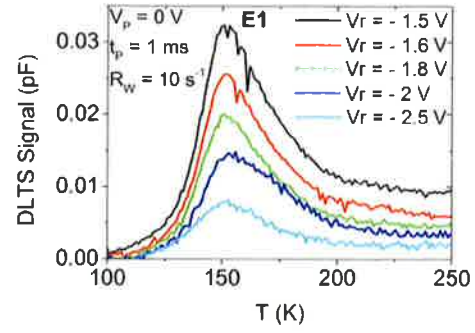


Fig. 5. (Color online) DLTS spectra of the recessed gate SBD for V_R varying from -1.5 to -2.5 V. The amplitude of the peak decreases, showing a reduction in defects concentration.

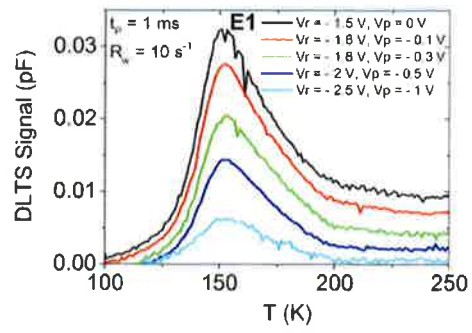


Fig. 6. (Color online) Evolution of the DLTS signal of the recessed gate SBD when the probe zone is shifted. $V_p - V_R$ is kept constant to 1.5 V. For $V_p = 0$ V, the probe zone is close to the GaN surface and moves towards the bulk when V_p is increased. By following this trend, the signal quenches.

moves towards the bulk when V_p is decreased. In Fig. 3, we see that the amplitude of the DLTS signal is not dependent on the filling pulse height. This behavior indicates that the defect concentration is constant inside the channel and that the defects are not interface-related.

In Fig. 5, we fixed the filling pulse height at $V_p = 0$ V and we changed the reverse bias from $V_R = -1.5$ to -2.5 V. When the reverse bias goes to more negative values, the probe region is deeper in the GaN bulk and we observe a quenching of the DLTS signal. This result allows us to conclude that the defects linked with trap E1 are mainly located in the upper part of the GaN layer.

This conclusion is consistent with the evolution of the DLTS signal in Fig. 6. By changing simultaneously the filling pulse height and the reverse bias, the probe zone is shifted from the surface towards the bulk. By going deeper and deeper inside the GaN layer, the amplitude of the signal quenches following an exponential law (Fig. 7). This trend confirms that the defects are mainly located in the upper part of the GaN layer.

In Fig. 8, we follow the shape evolution of the signal as a function of the filling pulse duration t_p . A new peak (labeled E2) emerges at 218 K for t_p larger than 5 ms and the maximum of the dominating peak E1 moves to lower temperature when t_p increases. Using several rate windows R_w between 5 and 2000 s $^{-1}$, we extracted from the Arrhenius plots reported in Fig. 9 the activation energy and the apparent capture cross-section of traps E1 and E2, with the data summarized in Table I.

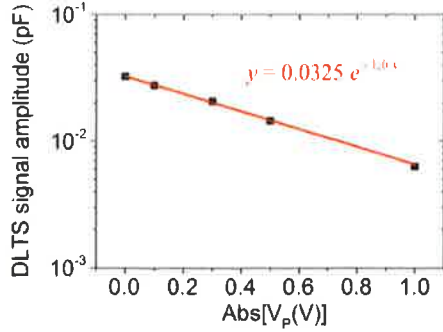


Fig. 7. (Color online) Evolution of the maximum DLTS amplitude versus the absolute value of V_p deduced from data in Fig. 6. The points are well fitted with an exponential law.

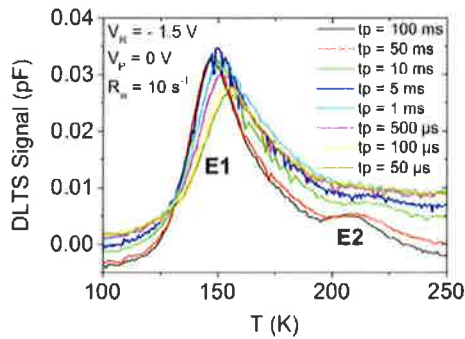


Fig. 8. (Color online) Evolution of the DLTS signal of the recessed gate SBD as a function of the filling pulse duration. Whereas only one peak is clearly visible near 150 K for small t_p , a second peak near 218 K appears for t_p larger than 5 ms.

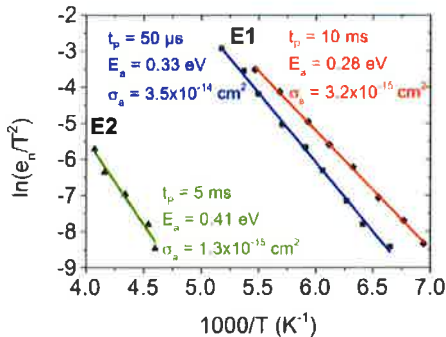


Fig. 9. (Color online) Arrhenius plots extracted from DLTS data in Fig. 8 ($V_R = -1.5$ V and $V_p = 0$ V) with nine rate windows varying from 5 to 2000 s $^{-1}$ with $t_p = 50$ μ s (squares) and $t_p = 10$ ms (diamonds) for trap E1 and with five rate windows varying from 10 to 200 s $^{-1}$ with $t_p = 5$ ms (triangles) for trap E2.

The shift of the peak E1 when increasing t_p can be explained by the presence of two traps composing E1 that we labeled E1a and E1b. Trap E1a was observed in GaN by several groups with an activation energy $E_a = 0.23$ – 0.3 eV.^{15,17–23} This trap is found to be “bulk” in nature^{15,24} but its concentration is strongly enhanced towards the surface after sputter deposition²⁰ or following ICP-RIE under high etching bias.¹⁵ Trap E1b can be observed as a high-temperature shoulder on E1 and is responsible for the asym-

Table 1. Activation energies and apparent capture cross sections of traps E1 and E2 extracted from Fig. 9.

Trap	Filling pulse width (t_p)	Energy level (eV)	Capture cross section (cm 2)
E1	50 μ s	$E_C - 0.33$	3.5×10^{-14}
E1	10 ms	$E_C - 0.28$	3.2×10^{-15}
E2	5 ms	$E_C - 0.41$	1.3×10^{-15}

metrical shape of the peak. This trap is reported in the literature with an activation energy $E_a = 0.34$ – 0.4 eV^{15,20–26} in GaN and is “near-surface” in nature.^{15,24} Traps E1a and E1b are associated with RIE-induced surface damage^{15,17,24–26} and are related to point defects which can behave as line defects when aligned along dislocations.^{15,25} Traps E1a and E1b are not affected by electron irradiation²⁷ and have been assigned to defects related to nitrogen vacancies as a complex.²⁵ Trap E1a was associated with dislocations²⁸ and Fang et al.²⁹ suggested that traps E1a and E1b are complexes which are segregated around dislocations.

It can be noted from Fig. 8 that the increase of the filling pulse width t_p leads E1 to be narrower and shifted to lower temperatures. Increasing t_p , E1a rises faster than E1b and dominates the spectrum.¹⁵ Hence, the activation energy of E1 decreases, becoming closer to the activation energy of trap E1a. Moreover, it is worth noting from Fig. 8 that E1 saturates for t_p larger than 1 ms. Such a behavior is consistent with point defects as expected for traps E1a and E1b.

In Fig. 8, the maximum of the broad peak labelled E2 is shifted to lower temperatures when t_p increases. This trend is compatible with a distribution of energy states. The shift of the maximum results from a broadening on the low temperature side of the peak as the fill-pulse time increases.³⁰ Trap E2 is close to trap ES4 observed by Auret et al.^{20–23} in GaN which has a band-like energy distribution. This trap has been assigned to complexes related to surface defects induced by ion penetration.²⁰

Following the above analysis, this work reveals that a partial etching of the AlGaN layer produces damage on the top of the underlying GaN layer.

4. Conclusions

The effect of an ion-assisted gate recess process in AlGaN/GaN SBD has been investigated using DLTS measurements. We demonstrated that three electron traps appear in GaN below the Schottky contact, after a partial etching of the upper AlGaN layer. These traps have been found in the energy range 0.28–0.41 eV under the minimum GaN conduction band. Their concentration is relatively constant in the first tens of nanometers, then decreases following an exponential law towards the buffer. Consequently, the three traps are mainly located in the two-dimensional electron gas channel, i.e., in the upper part of the GaN layer. It is likely that the defects are related to nitrogen vacancies as a complex and can behave as extended defects when decorating dislocations. Thus, we demonstrated that an ion-assisted gate recess process leads to the formation of deep states in the GaN bandgap which may impact the diodes performance due to trapping effects.

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