On the Identification of Buffer Trapping for Bias-Dependent Dynamic R_{ON} of AlGaN/GaN Schottky Barrier Diode With AlGaN:C Back Barrier

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***Abstract*— In this letter, we identified a dominant buffer trapping causing a bias-dependent dynamic R_{ON} for AlGaN/GaN Schottky barrier diodes (SBDs) fabricated on a C-doped AlGaN buffer as back-barrier. Current transient measurements at various temperatures were performed simultaneously on an AlGaN/GaN SBD and a transmission line model (TLM) structure based on the AlGaN/GaN heterojunction. During the stress of the TLM structure, the two Ohmic contacts are biased at the same voltage forming an equipotential surface while creating a uniform vertical electrical field to induce buffer trapping. We extracted the same dominant trap level of $E_C - 0.60$ eV from the current transient spectroscopy on both the AlGaN/GaN SBD and the TLM structure after stressing at −100 V, indicating that the increase in the dynamic R_{ON} of the diode is due to the electron trapping in the buffer layers. More electron filling of this buffer trap occurs at higher stressing voltages (from −50 to −200 V), which reflects in an enhanced current-transient amplitude at the same time-constant under higher stressing voltages.**

***Index Terms*— AlGaN/GaN, SBD, TLM, current collapse, dynamic R_{ON}, trap spectra, buffer trapping.**

I. Introduction

OVER the last few years, high voltage AlGaN/GaN lateral Schottky barrier diodes (SBDs) grown on silicon substrate have been demonstrated as promising candidates for next-generation high-efficiency power switching applications due to their excellent material properties [1]–[4]. One of the prominent features of AlGaN/GaN heterojunction is the formation of high-density two-dimensional electron gas (2DEG) at the AlGaN/GaN interface due to the spontaneous and piezoelectric polarization without intentional doping [5]. However, electron trapping effects in AlGaN/GaN heterostructures grown on foreign substrates can be limiting factors degrading the superior properties of 2DEG and the performance of the device [6]–[9].

Current collapse phenomena and dynamic R_{ON} increase of AlGaN/GaN SBDs were reported due to electron trapping under the off-state stressing pulse condition [10]. In the off-state operation of the diode, electron trapping at the AlGaN barrier surface or in the GaN/AlGaN buffer layers can be induced due to the presence of both lateral and vertical electric field in the depletion region. In previous work, we presented a combined off-state stress and current transient measurements on lateral AlGaN/GaN SBDs to understand the trapping mechanisms at the AlGaN surface and buffer layers [11]. However, a spatial-resolved spectroscopic technique for assessing the diode trapping mechanisms is still missing due to the non-uniform E-field in the depletion region.

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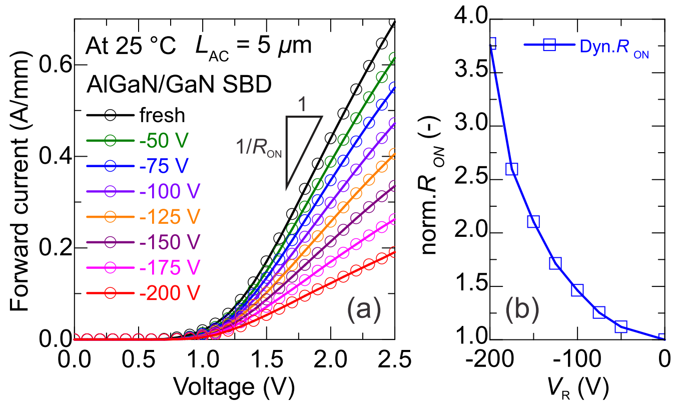

Fig. 1. (a) Typical pulsed forward characteristics of AlGaN/GaN SBD with a variation of reverse stressing pulse measured at 25 °C. Each forward point is preceded by the stressing pulse for 10 ms, and the rising time from the stressing pulse to the forward pulse is ∼2 ms. (b) The dynamic R_{ON} (normalized to the fresh value) with reverse stressing pulse V_R.

In this work, we spatially discriminate the traps located in the buffer from the ones at the AlGaN surface by performing current transient measurements simultaneously on AlGaN/GaN SBD and AlGaN/GaN transmission line model (TLM) test structure. We identified buffer trapping as the dominant mechanism causing a bias-dependent trapping phenomenon in AlGaN/GaN SBDs fabricated on intentionally C-doped AlGaN back barrier. Furthermore, we show that more severe R_{ON} increase of the AlGaN/GaN SBD stressed at higher voltages is due to more electron filling of the same buffer trap at the energy level of $E_C - 0.60$ eV.

II. Experimental Details

AlGaN/GaN active layers were grown epitaxially on 200 mm diameter Si wafer by metalorganic chemical vapor deposition (MOCVD). The epi-stack consists of 10 nm $Al_{0.25}Ga_{0.75}N$ barrier, a 150 nm GaN channel layer,

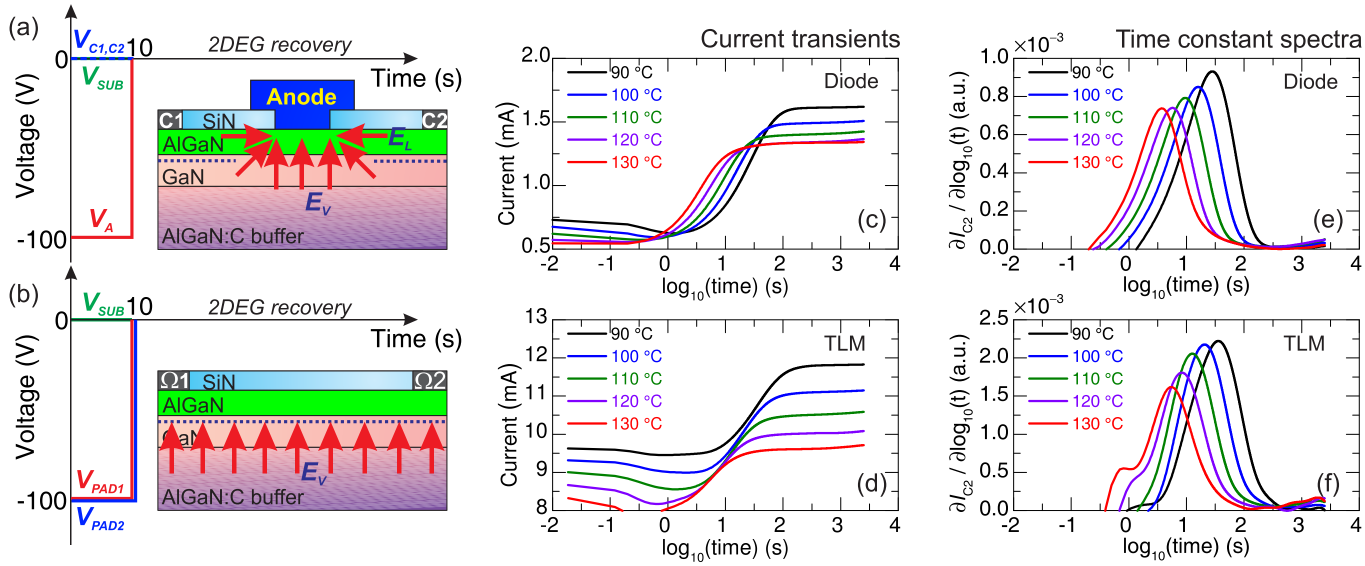

Fig. 2. The stress procedure and corresponding electric field distribution for AlGaN/GaN SBD (a) and AlGaN/GaN TLM structure (b). The current transient curves for diode (c) and TLM structure (d). The time constant spectra for diode (e) and TLM structure (f).

a 2.8-μm AlGaN buffer stack (from bottom to top: 500 nm $Al_{0.75}Ga_{0.25}N$, 500 nm $Al_{0.44}Ga_{0.56}N$, and 1800 nm C-doped $Al_{0.08}Ga_{0.92}N$), and a 200 nm AlN nucleation layer on *p*-type Si(111) substrates. The C-doped ($\sim 2\times10^{19}$ cm^{-3} measured by SIMS) AlGaN buffer as the back barrier was grown at 980 °C and was intended to suppress the buffer leakage and enhance the breakdown voltage [12], [13]. The capping layer of the wafer was 5-nm Si_3N_4 grown in the MOCVD chamber. The entire stack was then encapsulated by 140 nm Si_3N_4 layer by means of rapid thermal chemical vapor deposition (RTCVD). The removal of the Si_3N_4 passivation layer was performed by SF_6 dry etching. The Au-free anode metal was composed of a TiN-based stack, and a stack of Ti-based metals was used for the cathode contact formation [4]. The Schottky contact length (L_{SC}), the anode finger width, and the anode-to-cathode distance (L_{AC}) were 9 μm, 100 μm, and 5 μm, respectively. Thus the spacing between two cathode contacts in the AlGaN/GaN SBD is 19 μm. The AlGaN/GaN TLM test structure composed of two ohmic contacts with the 2DEG was also fabricated on the same wafer, and the separation of the two ohmic pads is 6 μm.

III. Results and Discussion

To characterize the dynamic characteristics of AlGaN/GaN SBD, pulsed current–voltage (*I*–*V*) measurements were performed by using a Semiconductor Device Analyzer Agilent B1505A [10]. The typical pulsed forward characteristics of the SBDs can be shown in Fig. 1(a). Each point of the forward characteristics is preceded by a 10-ms quiescent stressing pulse at a negative bias V_R (from 0 to -200 V) [10], the rising time from the quiescent point to the forward bias point is $\sim$2 ms. As is shown in Fig. 1(b), the dynamic R_{ON} (normalized to the fresh value) increases with the stressing voltages. After a pulsed stress at -200 V, the dynamic R_{ON} of the diode becomes 3–4 times of the fresh value resulting in a clear current reduction. This phenomenon is normally regarded as "current collapse" or on-resistance increase.

In our previous work, we developed a combined technique of off-state stress and current transient measurements on the diode test structure to understand the trapping/de-trapping characteristics [11]. As is displayed in Fig. 2(a), the anode contact is biased at -100 V with the cathode and substrate grounded during stress. In this stress state, the 2DEG channel is depleted in the vicinity of the anode contact. That creates a vertical as well as a lateral electric field which can result in electron trapping at the AlGaN surface, in the AlGaN barrier, or in the GaN channel and buffer layers. To understand the trapping mechanism shown in Fig. 1, we used an additional AlGaN/GaN TLM test structure fabricated on the same wafer, as shown in Fig. 2(b). During the stress, the two Ohmic pads in AlGaN/GaN TLM structure were biased at the same potential of -100 V. In this case, the 2DEG channel is un-depleted and in equipotential while a uniform and pure vertical *E*-field is generated to induce only electron trapping in the GaN channel or buffer layers (below the 2DEG).

The recovery of 2DEG current for AlGaN/GaN SBD and TLM structure after 10-s stress have been performed from 90 to 130 °C with results shown in Fig. 2(c) and Fig. 2(d), respectively. After recovery time of 3500 s, both the SBD and TLM structure recover back to the fresh condition and the transient curves become flattened out. The time constant spectra (the derivative of the current transients) of SBD and TLM structure were shown in Fig. 2(e) and Fig. 2(f), respectively. As is shown, the time-constant at the same temperature reveals to be almost the same for SBD and TLM structure. The Arrhenius plot for SBD and TLM can be generated based on the time-constants revealed in Fig. 2(e) and Fig. 2(f). As confirmed by the result shown in Fig. 3, the same trap level $\sim$0.60 eV was extracted from SBD and TLM structure, respectively. This indicates that the trap causing the diode R_{ON} increase at V_R of -100 V is located in the buffer layers.

In literature, different trap levels were extracted in AlGaN/GaN heterostructures with carbon-doped buffer [14]–[16]. The incorporation of carbon into the buffer

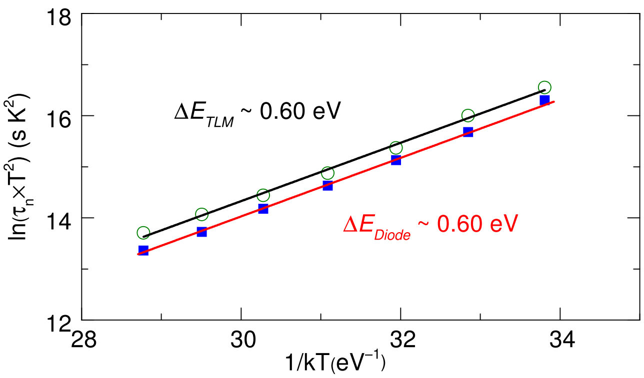

Fig. 3. Arrhenius plot of the time constant spectra performed on the diode and TLM structure.

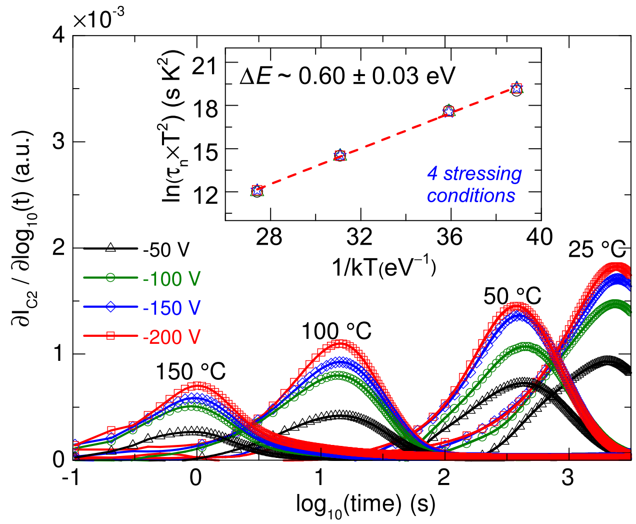

Fig. 4. Time constant spectra for AlGaN/GaN SBD after a reverse stress voltage (from −50 to −200 V) performed at 4 different temperatures. The inset graph confirms the trap activation energy ~0.60 eV involved under 4 different stressing conditions.

was controlled by the growth pressure in Ref. [14], [17] or the growth temperature in our case and in Ref. [16], the different growth conditions can result in different trap states. The origin of this trap may not be directly related to carbon dopants but native defects (i.e. vacancies, anti-sites, dislocations, etc.) which were generated during the epitaxial growth of carbon doped buffer [16]. Tanaka *et al.* reported the trap at 0.61 eV which is responsible for nitrogen anti-site defect [17]. Though many groups have extracted a trap level ~0.60 eV causing the recoverable degradation in GaN HEMTs with carbon doped buffer, the insight on the physical origin of this trap is still lacking. Moreover, the de-trapping kinetics may be associated with the buffer transport mechanisms which can have an impact on the extracted trap levels [18].

As shown in Fig. 1(b), the dynamic R_{ON} of the AlGaN/GaN SBD is bias-dependent. This can be due to the electron filling the same buffer trap or other traps at different locations. We performed current transient measurements on AlGaN/GaN SBD structure after a reverse stress voltage (from −50 to −200 V) at 4 different temperatures (from 25 to 150 °C). The time constant spectra for the SBD stressed at 4 different voltages are presented in Fig. 4. The curves show an enhanced current-transient amplitude at the same time constant under higher stressing voltages. This holds true for 4 different temperatures. It indicates that more trap states (at the same trap level) are filled at higher stressing voltages; that qualitatively explains the bias-dependent R_{ON} degradation in AlGaN/GaN SBDs. The bias-dependent amplitude in Fig. 4 shows different characteristics comparing with the results in Fig. 1(b), because the current measured in the transients was the entire 2DEG current instead of the diode forward current which is more sensitive to the 2DEG variation in the access region. The inset graph in Fig. 4 shows the same trap level of ~0.60 eV extracted for these 4 different stressing conditions. This result suggests that the more severe R_{ON} degradation at higher stressing voltages is due to more electron filling the buffer trap at activation energy of ~0.60 eV.

IV. Conclusion

In conclusion, a comparison of trap spectra for AlGaN/GaN SBD and AlGaN/GaN TLM structure has been performed using combined stress and current transient measurements. We identified a single dominant $E_C - 0.60$ eV trap in both AlGaN/GaN SBD and TLM structure indicating that the physical location of that trap is within the buffer layer. The bias-dependent R_{ON} increase of AlGaN/GaN SBD is due to more electron-filling of the $E_C - 0.60$ eV trap in the buffer, which has been confirmed by the observation of an enhanced current transient amplitude for the diode under higher stressing voltages.

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