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Effects of Deep Trapping States at High Temperatures on Transient Performances of AlGaN/GaN HFETs

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1. Introduction

AlGaN/GaN heterojunction field effect transistors (HFETs) are promising for power switching applications, which can be operated at high temperatures even at 300^{o}C[1]. So far, transient switching characteristics of the GaN devices have been affected by the trapping states, where the transient on-state resistance is increased from the DC value[2]. Elevating the ambient temperatures would activate the deeper trapping states resulting in change of the transient behaviors. Thus, the high temperature characteristics are the potential concern; however the effect of deep states on it has never been examined in detail.

In this paper, we investigate the transient performances of normally-off AlGaN/GaN HFETs at high temperatures up to 125^{o}C. It is experimentally found that the increase of on-state resistance R_{ON} right after the *on* switching from the *off* state is worsened at higher temperatures. The obtained result seems to be anomalous based on the expectation that the increase in the R_{ON} should be rather suppressed at higher temperatures owing to the enhanced electron emission. The activation energies of the trapping states extracted from the experiments indicates that there exists a potential barrier of 0.17eV for the capture of electrons. The proposed barrier model well explains the worsened performances at high temperatures.

2. Experimental

The GaN devices characterized in this study are normally-off AlGaN/GaN HFETs on Si substrates with p-AlGaN gate as shown in Fig.1. The transient switching characteristics are measured using the experimental set-up as shown in Fig.2(a), where a high drain voltage V_{DD} of 132V is applied. Since the increase in the on-state R_{ON} is originated from the trapped electrons induced by the off-state electric field (Fig.1) [2], the temporal behavior measurement of the R_{ON} enables us to investigate the electron trap and emission process. The electron emission process is investigated by the decay of R_{on} after the switching from the *off* to *on* state at various temperatures up to 125^{o}C, as shown in Fig. 2(b). The electron capture process is investigated by monitoring R_{on} in the off-on-off switching with a variation of *off* duration time t_p. Based on the experimental results, the characteristic time constants of the decay for the emission and capture of the electrons are extracted as τ_e and τ_c, respectively by the curve-fitting to the stretched exponential decay function in Figs.2(b) and (c). The activation energies for the both as ΔE_e and ΔE_c are also extracted.

3. Results and Discussion

Figure 3(a) shows the temporal decay curves of the R_{on} for the switching from *off* to *on*-state. It is experimentally found that the R_{on} right after the turning-*on* is significantly increased as the increase in the temperatures, which is contrary to the expectation from the enhanced emission of the electrons at the elevated temperatures. Figure3(b) shows the increase of the R_{on} after 100μs from the turning-*on* (ΔR_{ON}) normalized by the DC value (R_0) at each temperatures, where ΔR_{ON} is worsened at higher temperatures. In addition, the Arrhenius plot of the extracted τ_e in Fig.3(c) indicates that the activation energy required for the thermal emission of electrons from the trapping state, ΔE_e, is determined to be 0.78eV. Explanation on the above results should require a new model different from the conventional one in which only with the thermally activated emission of the electrons from the trapping states is taken into account.

In addition, the electron capture process is examined by varying t_p as shown in Fig.2(c). The increase of the R_{on} after 100μs from the *off*-pulse is plotted in Fig.4(a). The activation energy required for the electrons to be captured, ΔE_c, is extracted from the temperature dependence of τ_c, which is determined to be 0.73eV as shown in Fig.4(b). Since the capturing rate is expressed by $1/\tau_c = J\sigma_c/q$, where J, σ_c, and q are the flowing current, the capture cross section, and the elementary electric charge, respectively, the activation energies should have the relationship as $\Delta E_c = \Delta E_J + \Delta E_\sigma$. The activation energy of the current ΔE_J is extracted from the temperature variation of the leakage current of the device to be 0.56eV. Thus, the activation energy of the capturing process ΔE_σ is extracted to be 0.17eV, indicating the existence of a potential barrier for the electron capture process.

Based on the above experimental results, we propose a new model to explain the transient performances of the AlGaN/GaN HFETs at high temperatures, as summarized in Fig.5. The model includes the potential barrier of 0.17eV for the capturing at the deep state (Fig.5(a)) with the barrier of 0.78eV for the emission, as is observed in the DX centers in AlGaAs[4]. The proposed barrier for the electron capture is well understood in terms of the coordinate energy diagram as shown in Fig.5(b). The proposed barrier for the capture of electrons explains the experimentally observed transient performance which is worsened at higher temperatures.

4. Conclusions

We investigate the transient performances of normally-off AlGaN/GaN HFETs at high temperatures. Increase of on-state resistance right after the *on* switching from the steady state is worsened at higher temperatures, on the contrary to the expectation that the emission of the electrons are enhanced at the elevated temperatures. The model including the potential barrier of 0.17eV for the electron capturing at the deep state is proposed, which well explains the measured transient performances at high temperatures.

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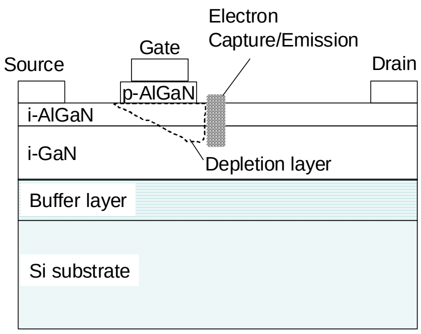

Fig. 1 Schematic cross section of the examined normally-off AlGaN/GaN HFETs at the *off* state. The increase in R_{on} after the *off* state is originated from the electrons capture/emission process induced by a strong electric field at the edge of depletion layer.

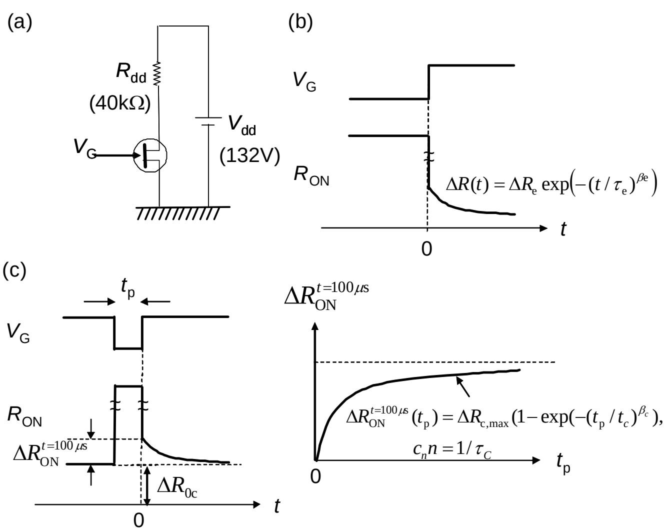

Fig.2 Experimental set-up and pulse configurations for the measurements of the transient performances of the fabricated AlGaN/GaN HFETs, (a) circuit diagram, pulse configuration, and formula to extract the decay constant for (b) electron emission, (c) electron capture.

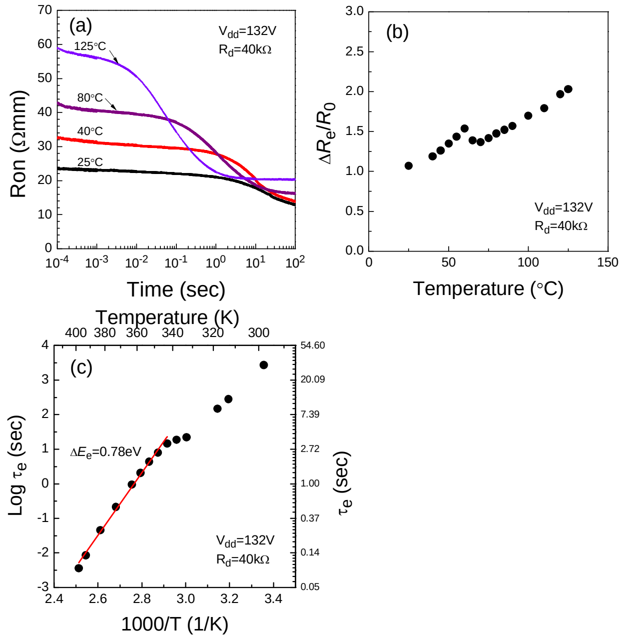

Fig.3 Transient performances to characterize the emission of the electrons, (a) temporal decay curve of R_{on} at various temperatures, (b) increase in the R_{on} after 100μs from the turning-*on* (ΔR_e) normalized by the DC value R_0, (c) Arrhenius plot of the extracted τ_e.

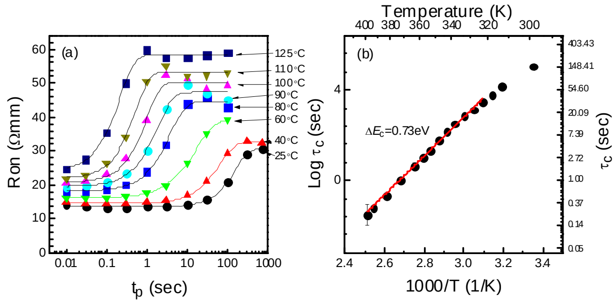

Fig.4 Transient performances to characterize the capture of the electrons. (a) R_{on} after 100μs of the *off*-pulse for various pulse width t_p, (b) Arrhenius plot of the extracted τ_c.

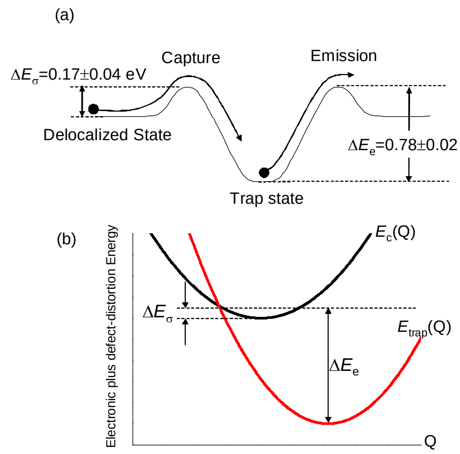

Fig.5 (a) Schematic energy diagram of capture and emission process in the AlGaN/GaN HFETs. (b) Configuration coordinate diagrams of the electronic and elastic energies at the trapping state and the conduction band. Here $E_C(Q)$ and $E_{trap}(Q)$ are the sum of the electronic and elastic energies of the conduction band and the deep level, respectively, as a function of configuration coordinate Q.