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Analysis of Deep Traps at Al_2O_3/n-GaN Interface using Photo-assisted C-V Measurement

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Abstract

We discussed the deep traps at Al_2O_3/n-GaN interface from V_{fb} shift after photo-irradiation ($h\nu$ = 3.3 eV) in depletion. The V_{fb} of all Pt/Al_2O_3/n-GaN capacitors shifted toward negative direction after photo-irradiation. The negative V_{fb} shift is dominantly due to the deep traps excited by photo and the estimated densities of the deep traps were 1.5 ~ 0.67 × 10^{12} cm^{-2} at PDA 600 ~ 900 °C.

1. Introduction

GaN-based vertical MOSFETs on free-standing GaN substrates have been widely investigated for next-generation GaN power devices [1]. To reduce the leakage current, MOS structures with Al_2O_3 and SiO_2 insulators were employed. To understand characteristics of insulator/GaN interface, the flat-band voltage (V_{fb}) shift, V_{fb} hysteresis and frequency dispersion were examined using capacitance-voltage (*C-V*) measurements. Many reports pointed out the evaluation of interface state density (D_{it}) in the energy levels close to the conduction band edge (E_C) using the conductance and the Terman methods [2, 3]. To evaluate D_{it} in the energy levels near midgap for Al_2O_3/AlGaN/GaN power device, photo-assisted *C-V* measurement was employed [4]. However, the deep traps in the deep energy levels near the valence band edge (E_V = 3.4 eV) of Al_2O_3/n-GaN has not been extensively studied.

In this study, we examine V_{fb} change of Pt/Al_2O_3/n-GaN MOS capacitors using photo-assisted *C-V* measurement and discuss the deep traps at Al_2O_3/n-GaN interface.

2. Experimental

Pt/Al_2O_3/n-GaN MOS capacitors were fabricated as follows. A 5-μm-thick Si-doped GaN epilayer (2 × 10^{16} cm^{-3}) on freestanding n^+-GaN(0001) (1.3 × 10^{18} cm^{-3}) was used as substrate. After cleaning the surface of the substrate in the solution of a sulfuric acid peroxide mixture (H_2O_2:H_2SO_4 = 1:1) for 5 min, a 25-nm-thick Al_2O_3 film was deposited by ALD at 300 °C using a TMA precursor and H_2O gas. Post-deposition annealing (PDA) was performed at 600 - 900 °C in N_2 atmosphere. Finally, 100-nm-thick Pt gate electrodes were deposited on the Al_2O_3 film through a shadow mask and Pt(100 nm)/Ti(20 nm) ohmic contacts were deposited on the backside of n^+-GaN substrate.

Fig. 1 shows schematic illustrations of band diagram for Al_2O_3/n-GaN gate stack during (a) typical *C-V* measurement in darkness and (b) photo-assisted *C-V* measurement. A semiconductor laser ($h\nu$ = 3.3 eV) was used as the light source. In **Fig. 1 (a)**, the gate bias was swept from accumulation (V_{fb}+3 V) to depletion (V_{fb}-3 V) (Initial) and kept for 60 s in darkness to examine shallow traps in the energy levels near E_C. Next, we restarted the *C-V* sweeping toward accumulation (V_{fb}+3V) (Darkness). On the other hand, in **Fig. 1 (b)**, after sweeping from accumulation to depletion, light was irradiated on the capacitor for 60 s to examine the deep traps which was excited by photo-irradiation in wider energy levels (E_C ~ E_V). After switching off the light, we restarted the *C-V* sweeping toward accumulation in darkness ($h\nu$).

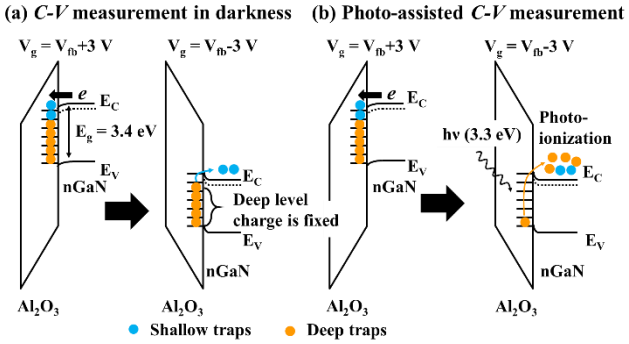

Fig. 1 Schematic illustrations of band diagram for Al_2O_3/n-GaN gate stack during (a) typical *C-V* measurement in darkness and (b) photo-assisted *C-V* measurement.

3. Results and Discussion

Fig. 2 shows *C-V* characteristics of Pt/Al_2O_3/n-GaN MOS capacitors. As-grown capacitor shows a very similar *C-V* behavior of the 600 °C capacitor. The *C-V* curves shifted in the positive direction as PDA temperature increased from 600 to 900 °C. **Fig. 3** shows *C-V* characteristics of the 700 °C capacitor under darkness and photo-irradiation conditions. The *C-V* curve of Darkness slightly shifted toward negative direction (-90 mV) (**Fig. 3 (a)**). The *C-V* shift is dominantly due to the shallow traps of short time constant near E_C. On the other hand, a large negative *C-V* shift (-640 mV) appeared after photo-irradiation (**Fig. 3 (b)**). Here, the deep traps of long time constant must be excited from the interface state in the wider energy levels by the photo-irradiation with the higher energy like the band diagram in **Fig. 1 (b)**.

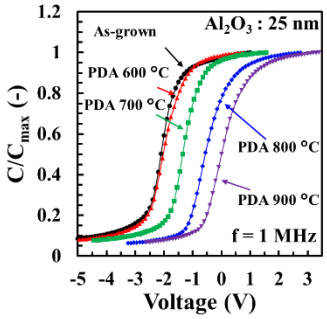

Fig. 2 *C-V* characteristics of Pt/Al_2O_3/n-GaN MOS capacitors. *C-V* curves shifted toward positive direction as PDA temperature increases from 600 ~ 900 °C.

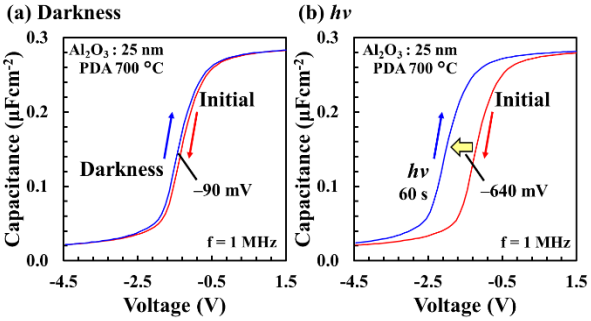

Fig. 3 *C-V* characteristics of the 700 °C capacitor under (a) darkness and (b) photo-irradiation conditions. A small negative shift of *C-V* curve of Darkness was observed because of shallow traps near Ec. A large negative shift of *C-V* curve of *hv* occurred due to deep traps in wider energy (E_C ~ E_V).

Fig. 4 shows V_{fb} changes of the Initial, Darkness and *hv* as a function of PDA temperature. V_{fb} of Initial ($V_{fb\ Initial}$) shifted toward ideal V_{fb} as PDA temperature increases, indicating that characteristics at Al_2O_3/n-GaN interface was significantly improved. The effect of PDA treatment on electrical properties of the Al_2O_3/n-GaN MOS capacitors were reported [2, 5]. The difference between the V_{fb} of Darkness ($V_{fb\ Darkness}$) and the $V_{fb\ Initial}$ decreases from 0.1 V to 0.01 V as PDA temperature increases from 600 to over 700 °C. This suggests that the number of shallow traps near E_C becomes small because of improvement of Al_2O_3/n-GaN interface.

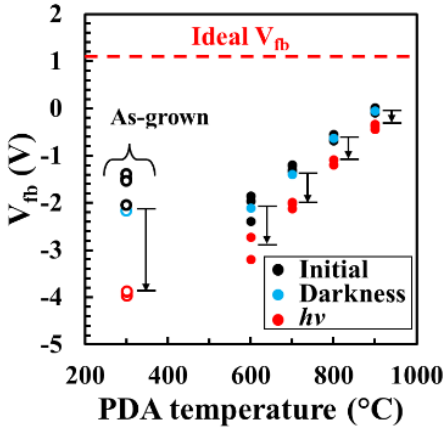

Fig. 4 V_{fb} changes of Pt/Al_2O_3/n-GaN MOS capacitors under several measurements (Initial, Darkness, and *hv*). The V_{fb} of *hv* shifted significantly toward negative direction compared to those of V_{fb} of Darkness in all capacitors.

Note that V_{fb} of *hv* ($V_{fb\ hv}$) shifted significantly toward negative direction compared to those of $V_{fb\ Darkness}$ in all capacitors.

Fig. 5 (a) shows the difference between the $V_{fb\ hv}$ and $V_{fb\ Darkness}$ as a function of PDA temperature. As-grown capacitor exhibited a large negative V_{fb} shift with -1.7 V. The negative V_{fb} shift decreases gradually with increasing PDA temperature. The negative V_{fb} shift is thought to be dominantly due to the deep traps in the deep energy levels near E_V because there are several interface states around E_V [6]. Here, we estimated density of deep traps according to equation (1),

$$D_{dt} = \frac{C_{ox}(V_{fb\ hv} - V_{fb\ Darkness})}{q}, \qquad (1)$$

which D_{dt} is density of deep traps, C_{ox} is oxide capacitance, and q is elementary charge, respectively. As shown in **Fig. 5 (b)**, as-grown capacitor shows a large D_{dt} of 3.1 × 10^{12} cm^{-2}, suggesting that the initial Al_2O_3 growth resulted in the formation of electrical defects on the surface of the n-GaN. Although the D_{dt} decreases as PDA temperature increases, a large density of 0.67 × 10^{12} cm^{-2} remains even after PDA 900 °C. We believe that the large number of deep traps in deep energy level must be related to device characteristics of mobility and threshold voltage.

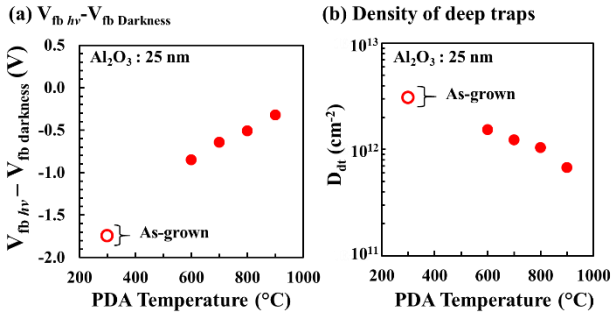

Fig. 5 (a) The difference between the $V_{fb\ hv}$ and $V_{fb\ Darkness}$ and (b) estimated density of deep traps as a function of PDA temperature. $V_{fb\ hv}$ - $V_{fb\ Darkness}$ decreases gradually with increasing PDA temperature. The estimated the density of deep traps were 1.5 ~ 0.67 × 10^{12} cm^{-2} at PDA 600 ~ 900 °C.

3. Conclusions

We studied V_{fb} shift due to the deep traps at Al_2O_3/n-GaN interface for Pt/Al_2O_3/n-GaN capacitors using photo-assisted *C-V* measurement. Negative V_{fb} shift was observed in all capacitors after photo-irradiation compared to those of typical *C-V* measurement in darkness. The negative V_{fb} shift due to the deep traps exhibited -0.32 V and the D_{dt} was estimated 0.67 × 10^{12} cm^{-2} at PDA 900 °C.

Acknowledgements

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References

[1] T. Oka et al., Appl. Phys. Express **8** (2015) 054101.
[2] T. Marron et al., Phys. Status Solidi C **9** (2012) 907.
[3] N. Taoka et al., Jpn. J. Appl. Phys. **57** (2018) 01AD04.
[4] C. Mizue et al., Jpn. J. Appl. Phys. **50** (2011) 021001.
[5] H. -S. Kang et al., J. Phys. D **46** (2013) 155101.
[6] T. Tanaka et al., Thin Solid Films **557** (2014) 207.