Correlation between Current Collapse Phenomena and Deep-Level Defects in AlGaN/GaN Hetero-Structures Probed by Deep-Level Optical Spectroscopy

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Abstract: We have investigated electronic deep levels in two AlGaN/GaN hetero-structures with different current collapses grown at 1150 and 1100 °C by a deep-level optical spectroscopy technique, using Schottky barrier diodes. Three specific deep levels located at ~2.07, ~2.80, ~3.23eV below the conduction band were found to be significantly enhanced for the severe current collapse, being in reasonable agreement with photoluminescence and capacitance-voltage characteristics. These levels probably originate in Ga vacancies and residual C impurities, and are probably responsible for the current collapse phenomena of the AlGaN/GaN hetero-structures.

Keywords: AlGaN/GaN hetero-structure, current collapse, deep level, deep-level optical spectroscopy

1. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs), utilizing a two-dimensional electron gas (2DEG) produced at the hetero-interface, are of great current interest due to their capability of operating at high power, high temperature, and high frequency. In general, these devices encounter undesirable current collapse issues, where actual device performances at high frequencies can be limited by the presence of deep-level defects in the AlGaN/GaN hetero-structures.1) i.e., electrical charge, trapped by the deep levels, modifies the 2DEG concentration in the channel and limits the switching characteristics of the devices. Although surface treatments on AlGaN top layer have already been reported to be effective in decreasing the current collapses by inactivating the surface states in AlGaN, the current collapses have yet to be completely eliminated.2) In order to reduce the promising potential of AlGaN/GaN HEMTs, it is needed to perform basic investigation of deep-level defects in AlGaN/GaN hetero-structures from a viewpoint of the current collapses. To date, a number of researchers have investigated these defects, using various characterization techniques such as photo-ionization spectroscopy, deep-level transient spectroscopy (DLTS), and deep-level optical spectroscopy (DLOS).3-6) However, a detailed correlation between the deep-level defects and the current collapses still remains uncertain. In this study, we have characterized electronic deep levels in AlGaN/GaN hetero-structures with different current collapses, employing capacitance-voltage (C-V) and capacitance DLOS techniques.

2. EXPERIMENTAL

Two AlGaN/GaN hetero-structures were grown on c-plane sapphire substrates at 1150 and 1100 °C, using metal-organic chemical vapor deposition (MOCVD), and are denoted by samples 1 and 2, respectively. The
growth pressure and III/V ratio were kept constant. They consisted of a GaN buffer layer, an unintentionally doped 3 μm-thick GaN layer, and an unintentionally doped 20 nm-thick AlGaN layer with an Al mole fraction of 24 %, as shown in Fig. 1. Both samples exhibited typical 2DEG properties, with a sheet carrier concentration of \( \sim 8 \times 10^{12} \) cm\(^{-2} \) and a mobility of \( \sim 1300 \) cm\(^2\)/Vs, as determined by room-temperature (RT) Hall-effect measurements. Photoluminescence (PL) measurements were also performed at RT to study optical properties of samples 1 and 2. The PL was excited by the 325 nm line of a He-Cd laser with an excitation power of 2 mW. After growth, the current collapses were simply assessed on SiN-passivated planar HEMT devices with gate length, gate width and channel length of 0.4, 100 and 5 μm, respectively, based on samples 1 and 2, stressing a source-drain voltage \( V_{SD} \) of -100 V for 5 min. Here, a gate voltage \( V_{GD} \) was kept at -10 V, where the 2DEG channels were fully pinched off. Samples 1 and 2 showed a decrease by \( \sim 34 \) and \( \sim 68 \) % in drain current \( I_{SD} \) at the \( V_{SD} \) of -20 V and the \( V_{GD} \) of 0 V, respectively, before and after the \( V_{SD} \) bias stressing. Additionally, to study electrical properties of samples 1 and 2 in detail, planar Schottky barrier diodes (SBDs) were fabricated on samples 1 and 2, using Pt as a Schottky metal. Pt metal dots were 0.9 mm in diameter. The fabricated Pt/AlGaN /GaN SBDs were characterized at RT by means of current density-voltage (\( J-V \)), \( C-V \), and DLOS measurements. Both SBDs based on samples 1 and 2 showed good rectifier characteristics from the \( J-V \) measurements in the dark. Additionally, the current collapses were roughly assessed on the SBDs without any SiN passivation. Photo and dark \( C-V \) measurements were performed at 100 kHz on the SBDs with/without white light illumination (\( \lambda > 380 \) nm) from the back side with a 150 W high-pressure Xe lamp. In both \( C-V \) measurements, a diode bias voltage \( V_G \) was applied and the capacitance were measured after a delay of 30 s. DLOS measurements were performed at 100 kHz, measuring photo-capacitance transients as a function of incident photon energy, from 0.78 eV (1600 nm) up to 4.0 eV (300 nm). The fabricated SBDs were illuminated from the back side with monochromatic light obtained from the same Xe lamp coupled with a high resolution monochromator and higher-order cut filters. The photo-capacitance transients were recorded for 300 s after the onset of illumination. The SBDs were maintained under reverse biased conditions, where the \( V_G \) was suitably chosen to determine the discretionary probing depth range in the AlGaN/GaN hetero-structures. Prior to optical excitation, the deep levels were filled with electrons in the dark by applying a forward voltage pulse of +1.0 V with a pulse width of 1.0 s, followed by a 5.0 s delay, in order to reduce any possible thermal transient contributions to the photo-capacitance. In this study, the DLOS signal is defined as \( \Delta C_{st}/C_0 \). Here, \( C_0 \) is the diode capacitance under the reverse biased condition in the dark, before the optical excitation, and \( \Delta C_{st} \) is the steady-state photo-capacitance which is determined as saturation values of their transients recorded at each wavelength. Also, the DLOS signal is not corrected by the excitation spectrum.

3. RESULTS AND DISCUSSION

Figure 2 shows typical atomic force microscopic (AFM) images of samples 1 and 2. Their RMS roughnesses
are ~0.41 and ~0.33 nm for samples 1 and 2, respectively. So, both samples show very smooth surface morphology regardless of different growth temperatures, suggesting that these samples deserve physical and electrical characterization as stated later.

Figure 3 shows typical PL spectra of samples 1 and 2. Both samples exhibit a broad yellow luminescence (YL) band around ~2.23 eV associated with a recombination between a shallow donor and a deep acceptor in addition to the band-edge (BE) emission of GaN at ~3.43 eV. The intensity ratios of yellow to band-edge luminescence, YL/BE, are 0.80 and 2.22 for samples 1 and 2, respectively. This experimental result supports that the magnitude of the current collapses depends on the YL/BE intensity ratio, being in reasonable agreement with previous study reported by Fujimoto et al. 8.}

Figure 4 shows typical J-V characteristics of samples 1 and 2, before and after long term bias stressing at $V_G$ of -30 V for 1 h. The bias-stressing-induced current attenuation ratios at $V_G$ of +2 V are estimated to be ~ 8 and ~33 % for samples 1 and 2, respectively. Considering that these values contain an influence of surface states in AlGaN, this experimental result is in reasonable with that on the SiN-passivated planar HEMT devices as stated above.

![AFM images of samples 1 and 2.](image1)

![Room-temperature PL spectra of samples 1 and 2.](image2)
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Typical dark and photo $C-V$ characteristics of the Pt/AlGaN/GaN SBDs are shown in the inset of Fig. 5. A small increase in capacitance with illumination can be clearly observed in both samples; compared to the dark $C-V$ characteristics, the photo $C-V$ ones shift a little more negatively in the partial pinch-off mode, reflecting an increase in 2DEG carrier concentration due to deep-level photoemission. Figure 5 shows the illumination-induced increase in capacitance, $\Delta C$, as a function of $V_G$. Samples 1 and 2 have maximum values at the $V_G$ of -2.29 and -2.44 V, respectively. From the integration of their corresponding $\Delta C$ peaks, the increased 2DEG carrier concentrations on illumination, $\Delta n_{2DEG}$, are estimated to be at least $7.4 \times 10^{10}$ and $1.5 \times 10^{11}$ cm$^{-2}$ for samples 1 and 2, respectively, and are considered to be optically excited from deep-level defects to the 2DEG at the AlGaN/GaN hetero-interfaces. Thus, sample 2 with the severe current collapse has two times higher concentrations of the deep-level defects than sample 1. This experimental result suggests that the deep-level concentrations are closely related to the current collapses, as well as the YL/BE intensity ratio of the PL spectra.

![Figure 4](image1.png)

**Figure 4.** Room-temperature $J-V$ characteristics of samples 1 and 2, before and after long term bias stressing at $V_G$ of -30 V for 1 h.

![Figure 5](image2.png)

**Figure 5.** Room-temperature $\Delta C-V$ characteristics of Pt/AlGaN/GaN SBDs based on samples 1 and 2. The inset shows dark and photo $C-V$ characteristics.
Figure 6 shows typical DLOS spectra of samples 1 and 2 at their corresponding peak $V_G$ of -2.29 and -2.44 V, respectively, as determined from the $\Delta C$-$V$ characteristics. Here, the probing depth ranges are ~62 and ~65 nm from the top surface of the AlGaN layers for samples 1 and 2, respectively. Both samples show five photoemission states with their onsets at ~1.42, ~2.07, ~2.34, ~2.80, and ~3.23 eV (T1, T2, T3, T4, and T5) below the conduction band, in addition to the near-band-edge (NBE) emissions from GaN at ~3.43 eV and AlGaN at ~3.87 eV. Also, ~1.77 eV level newly shows up in the DLOS spectra measured at low $|V_G|$ around -1.80 V for both samples. These deep levels exhibit dominant process of electron emissions to the conduction band due to their positive photo-capacitance transients, and are almost identical to the deep-level defects that have been previously reported for AlGaN/GaN hetero-structures.$^{5,6}$ From the $V_G$ dependence of their DLOS signals, these deep levels stem from the GaN layer rather than the AlGaN layer.$^5$ Particularly, bearing in mind that the ~2.07 and ~1.77 eV levels are enhanced with decreasing the $|V_G|$, these two levels are probably located near the AlGaN/GaN hetero-interface.$^6$ Among these deep levels, sample 2 with the severe current collapse obviously shows much higher concentrations of the ~2.07, ~2.80, and ~3.23 eV levels than sample 1, which is the same tendency as the $\Delta C$-$V$ and PL results. These specific levels are probably responsible for the current collapses observed in the AlGaN/GaN hetero-structures. In particular, a significant difference in the ~2.80eV level can be seen between samples 1 and 2. Additionally, negative photo-capacitance transients can be seen in the incident photon energy range between ~0.78 and ~1.35 eV for both samples, which likely indicates the presence of a hole trap.$^{4,6,9}$

AlGaN/GaN material properties strongly depend on the MOCVD growth conditions such as growth pressure, growth temperature, and III/V ratio.$^9$ In this study, the growth temperature is a key factor for their properties. In general, the C impurity incorporation tends to be enhanced at the low growth temperature, resulting in the deep-level formation of the residual C impurities and Ga vacancies ($V_{Ga}$). So, it is reasonable that sample 2 has higher deep-level concentrations than sample 1, as revealed by the PL, $\Delta C$-$V$, and DLOS measurements. Especially, the ~2.07, ~2.80, and ~3.23 eV levels observed in the DLOS spectra are considered to be closely related to the $V_{Ga^*}$ and the C impurity-induced levels; the ~2.07 and ~3.23 eV levels are respectively attributable to the $V_{Ga}$ and the shallow C acceptor ($C_N$) where C is substitutionally incorporated into the N lattice sites.$^{10}$ Also, the ~2.80 eV level originates in $V_{Ga}$-$C_N$ complexes and is probably associated with the YL band observed in the PL spectra.$^5$

Figure 6. Room-temperature DLOS spectra of Pt/AlGaN/GaN SBDs based on samples 1 and 2.
According to recent theoretical calculations by Van de Walle et al., this level may be closely related to the substitutional C states that they have predicted. The behavior of these specific deep-levels is likely in conjunction with each other due to their common origins. The ~3.23 eV level has an effect on decreasing the effective carrier concentration due to the shallow acceptor states, whereas the ~2.07 and ~2.80 eV levels probably act as trapping centers of carriers. So, the latter levels rather than the former are considered to be associated with the current collapse issues.

4. CONCLUSIONS

We have successfully characterized the electronic deep levels in two AlGaN/GaN hetero-structures with different current collapses grown at 1150 and 1100 °C, using the PL, $C-V$, and DLOS techniques. A clear difference in three specific deep levels located at ~2.07, ~2.80, ~3.23 eV below the conduction band can be seen between these samples. In particular, the ~2.07 and ~2.80 eV levels are probably responsible for the current collapse phenomena of the AlGaN/GaN hetero-structures.

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