Anomalous Decrease of Off-State Drain Leakage Current in GaN/AlGaN HEMTs With Dual Optical Excitation

Atanu Das, Danny Hsu Ko, Ray-Ming Lin, Liann-Be Chang, and Lee Chow

***Abstract*— We report an anomalous decrease of off-state drain leakage current ($I_{Off-state}$) of GaN/AlGaN HEMTs upon dual optical excitation. The phenomenon was observed accidentally during dc characterization of devices when both fluorescent white room light and incandescent optical microscope light were turned on. A similar phenomenon was observed and verified through simultaneous optical excitation of both ultraviolet (UV ∼350 nm) light and 532-nm green light. A spectrally resolved measurement revealed broad trap level centered ∼2.27 eV. The decrease of $I_{Off-state}$ during dual excitation is owing to the optical quenching of photoconductivity in GaN buffer layer. This quenching effect is originated from enhanced light-defect interaction, where sub-band gap light reduces photoconductivity induced by above bandgap light. Observation of this phenomenon would provide us an alternative way to characterize GaN buffer layer quality for the development of GaN HEMTs.**

***Index Terms*— Deep traps, GaN, HEMTs, optical excitation, off-state current.**

I. Introduction

GALLIUM nitride (GaN) based material system have been intensively studied over the past few decades [1], [2]. GaN materials are typically grown on sapphire or SiC substrate to which they are both lattice and thermally mismatched. Consequently, device grade GaN film possesses a high density of grain boundaries, dislocations and various point defects. Development in growth techniques of nitride based semiconductor have been achieved, resulting much lower density of structural defects [3]. In spite of the progress in growth techniques, the role of various defects in GaN and their substantial properties are not fully understood. The presence of optically-active defect known as 'yellow luminescence center' in almost all kinds of GaN samples independent to growth techniques indicates it to be the intrinsic origin [4]. Various anomalous phenomena like kink effect, current collapses during device operation were observed in GaN based HEMT [5]. However, most of the studies were focused on on-state drain current response with illumination, while the off-state drain current of those devices with illumination has rarely been investigated. In this letter, we report an anomalous decrease of off-state drain leakage current in GaN/AlGaN HEMT with dual optical excitation and the responsible trap level through spectrally resolved measurement was analyzed. A possible application of the observed phenomenon will also be mentioned.

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II. Experimental Procedures

The GaN/AlGaN heterostructure was grown on sapphire substrate by atmospheric pressure metal organic chemical vapor deposition (AP-MOCVD) system comprised of unintentionally doped (UID) 4 μm GaN followed by 25 nm $Al_{0.27}Ga_{0.73}N$ barrier layer. By means of Hall measurement, the sheet electron concentration and mobility are about 1.15×10^{13} cm^{-2} and 1130 cm^2.V^{-1}.s^{-1} respectively. The 'Round HEMT' with round shaped gate was fabricated for the electrical characterizations. The native oxide of exposed AlGaN surface was removed using dilute hydrochloric acid ($HCl:H_2O$ = 1:10) for 90 sec. Ohmic contacts were formed by electron beam (e-beam) deposition of Ti/Al/Ni/Au and a lift-off process followed by a rapid thermal annealing at 850^{o}C for 30 s in N_2 ambient. Finally, Ni/Au metals were e-beam evaporated and lifted off to form the gate electrodes. The current-voltage curve was measured by Agilent B1500A semiconductor parameter analyzer. Our initial observation was associated with dual optical excitation from the fluorescent white room light and optical microscope (OM) light. The OM light has a continuous spectral distribution ranging from 400∼900 nm with peak intensity in the 500∼700 nm region. The fluorescent white room light provides a broad range of photon energy covering band gap of GaN [6]. To understand the mechanism behind the anomalous decrease of $I_{Off-state}$, measurement was performed under dual optical excitation of precise wavelength. An ultraviolet (UV∼350 nm) light emitted from mercury vapor lamp with power density of 3 mW/cm^2 was used to initiate an above band gap optical excitation. Laser diodes with a wavelength of 532 nm∼2.33 eV and power density 63 mW/cm^2 was used to trigger a sub-band gap optical excitation. For spectrally resolved measurement, varying wavelength dispersed from Xenon lamp by a SpectraPro-300i spectral system was used.

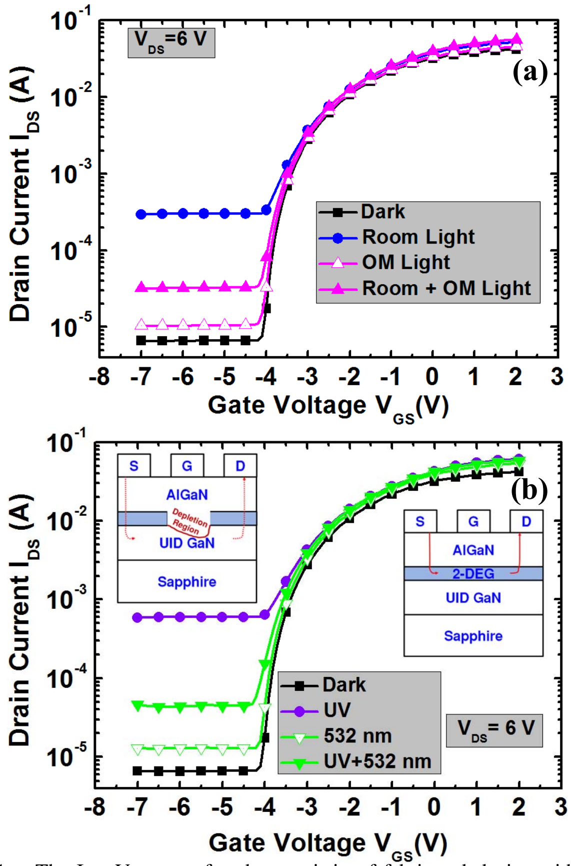

Fig. 1. The I_{DS}-V_{GS} transfer characteristic of fabricated device with dark and different optical excitation condition. (a) Initial observation showing anomalous decrease of $I_{Off-state}$ upon dual excitation of fluorescent white light and OM light; (b) showing $I_{Off-state}$ decrease by additional optical excitation of 532 nm light. [Inset: schematic illustration of GaN/AlGaN HEMT showing two conduction channel. (right) Current is flowing through 2-DEG during on-state; (left) current is flowing through parasitic conduction channel in buffer layer during off-state.].

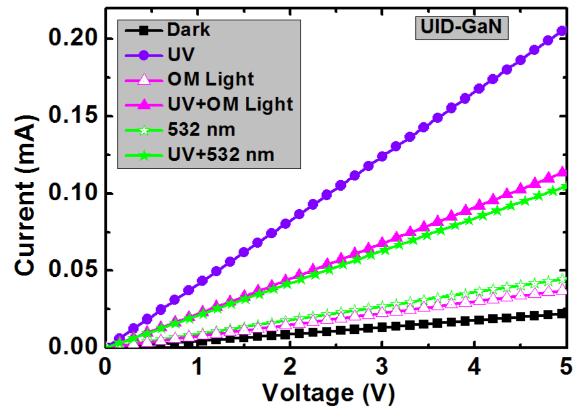

Fig. 2. Current-voltage characteristics of UID-GaN under dark and UV excitation showing optical quenching by additional 532 nm or OM light.

III. Results and Discussion

Fig. 1(a) depicts our initial observation regarding anomalous behavior of $I_{Off-state}$, where $I_{Off-state}$ owing to fluorescent white light is decreased under dual excitation of white light and OM light. A similar decrease is also observed under dual excitation of UV light and precise sub-band gap optical excitations of 532 nm as shown in Fig. 1(b). Inset of Fig. 1(b) schematically represents the two conduction channels in GaN/AlGaN HEMT. During on-state of device operation, the current is mainly flowing through 2-DEG conduction channel (right). But during off-state of device operation, current is flowing through a parasitic conduction channel formed in UID-GaN buffer layer (left). Variation of $I_{Off-state}$ with optical excitations is related to photo-ionization of carriers in GaN buffer layer and corresponding change of buffer layer resistance. The UV or white light causes an increase in $I_{Off-state}$ which is reasonable because it excites more carriers from valence band to conduction band. However, the additional sub-band gap light (OM light or 532 nm) with UV or white light causes a decrease in $I_{Off-state}$ which is anomalous, indicating an optical quenching (OQ) effect. To further verify the optical quenching effect, current-voltage measurement (Fig. 2) is performed under different optical excitation between co-plannar Ti/Al ohmic contacts on UID GaN grown in similar condition as GaN buffer layer in GaN/AlGaN heterostructure. The photo-current is decreased under dual excitations of UV + 532 nm and UV + OM light. It was reported [7] that the optical quenching occurs for sub-band gap light with energy from 1.2 eV to 2.6 eV. It ensures that the optical conductivity quenching in GaN layer is the origin of anomalous $I_{Off-state}$ behavior in GaN/AlGaN HEMT. It is noted that the $I_{Off-state}$ owing to OM only or 532 nm light ($I_{OM/532\ nm}$) is slightly higher than the current measured in dark ($I_{Dark.}$) [Fig. 1 and Fig. 2] which will be explained later.

Fig. 3(a) shows the real time response of $I_{Off-state}$ showing optical quenching (OQ) and persistent photoconductivity (PPC) effect. Fig. 3(b) shows the $I_{Off-state}$ response of GaN/AlGaN HEMT when two beams of monochromatic radiations were simultaneously illuminated. The first continuous photon energy of 3.54 eV generates free electron-hole pairs leading to an intrinsic photocurrent depicted by the dotted line in figure. The second photon energy is continuously varying from 3.5 eV to 1.5 eV. An increase in photocurrent with an absorption edge at 3.4 eV is observed. In addition, the photocurrent is quenched by photon energy from 1.5 eV to 2.6 eV, which shows a broad trap levels centered around 2.27 eV. As the quenching occurs for broad sub-band gap light with energy from 1.5 eV to 2.6 eV, the quenching light energies do not need to coincide with any sharp absorption edges. This is the reason why OM light with broad spectral distribution causes optical quenching during dual excitation (UV + OM light). As the UID-GaN is n-type in nature, only hole traps can cause optical quenching of photo-conductivity in UID-GaN. Semi-insulating GaN is obtained from considerable carbon doping during growth. We did not use intentional carbon doping to increase resistance of GaN buffer layer in our experiment. GaN grown by AP-MOCVD incorporates 10 times lower carbon than that of low pressure MOCVD [8] which exclude the possibility of carbon related acceptor states. The possible candidate for the hole trap is the gallium vacancy V_{Ga} predicted by several theoretical works [9] or nitrogen antisite (N_{Ga}) [6]. The V_{Ga} or N_{Ga} has multiple charge states and undergoes different charge states with structural relaxation during optical excitation.

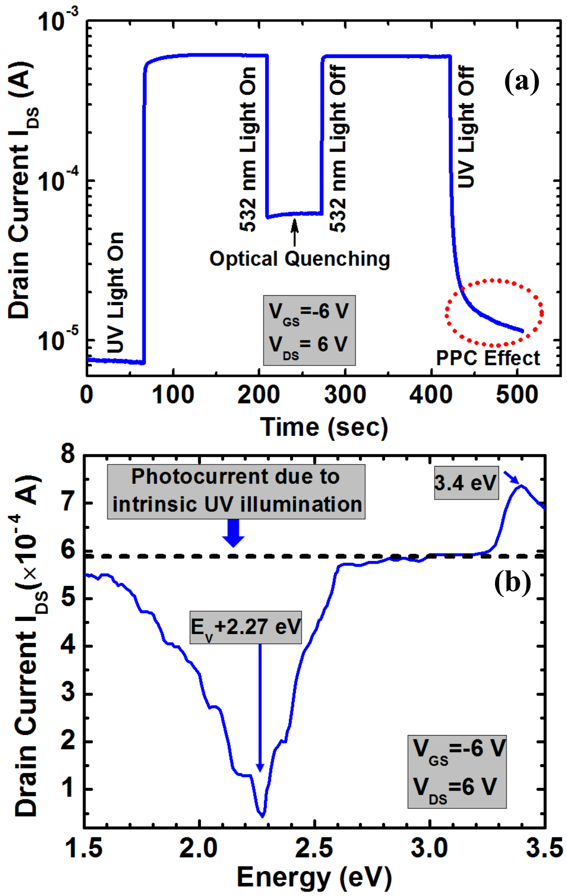

Fig. 3. (a) The $I_{Off-state}$ kinetics under excitation of UV and 532 nm light showing OQ and PPC effect. (b) $I_{Off-state}$ response under spectrally resolved measurements.

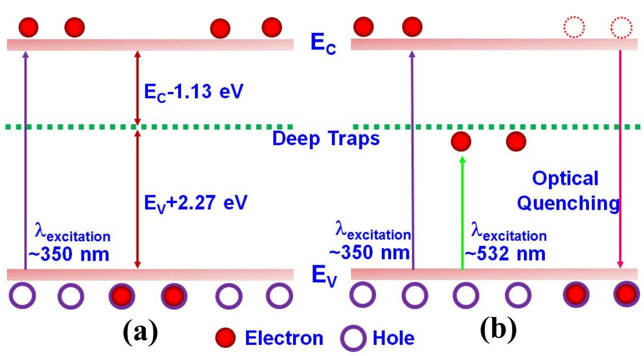

Fig. 4. Schematic illustration (not to scale) showing optical quenching effect in GaN layer during dual optical excitation. (a) Electron excited from valence band to conduction band with 350 nm above-band gap light; (b) quenching occurs upon the additional sub-band gap illumination of the 532 nm light.

The photo-carrier dynamics of the optical conductivity quenching effect can be further understood from the schematic illustration as shown in Fig. 4. First the 350 nm light builds up a stable background photo current by exciting electron from the valence band to the conduction band [Fig. 4(a)]; upon illumination of the sub-band gap light, excess holes are generated by promoting electrons from the valence band to the deep traps [Fig. 4(b)]. The generated holes in the valence band are then recombined with free electrons in conduction band, leading to a decrease in electron population and conductivity. The carrier transport processes triggered by simultaneous optical excitation from both UV and 532 nm light are not independent. The charge state of the trap level is altered after being emptied by UV illumination and readily captures electrons excited from the valence band by OM/532 nm light. As the trap level is broad in nature, we speculate that the same trap behaves differently i.e. $E_V + (2.6\sim1.2)$ eV centered at $E_V + 2.27$ eV causes OQ related anomalous decrease of $I_{Off-state}$ during dual optical excitation of (UV + OM/532 nm), on the other hand $E_C - (2.2\sim0.8)$ eV centered at $E_C - 1.13$ eV causes increase in photoconductivity (i.e. slight increase of $I_{Off-state}$ over I_{Dark} in Fig. 1 and Fig. 2) during only OM/532 nm light excitation and PPC effect.

We would like to point out that the decrease of $I_{Off-state}$ is minimal for high resistive GaN buffer [10] as compared to UID-GaN under dual optical excitation. The amount of current decrease would provide a simple characterization method which measures the degree of traps in GaN buffer layer.

IV. Conclusions

We have identified an anomalous off-state drain leakage current behavior in GaN/AlGaN HEMTs with dual optical excitation of fluorescent white light and optical microscope light. The origin of this anomaly is optical conductivity quenching effect in GaN buffer layer, which was verified through dual excitation of UV and 532 nm laser light. The responsible broad deep trap level centered at E_V+2.27 eV was found through spectrally resolved measurement. This dual optical excitation analysis seemed to be an alternative tool for the development of GaN epitaxial layer.

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