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Observing Electroluminescence from Yellow Luminescence-Like Defects in GaN High Electron Mobility Transistors

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A yellow band electroluminescence (EL) characteristic, which might be attributed to the same origin as the yellow luminescence (YL) defects, was observed in GaN high electron mobility transistors (HEMTs) at room temperature. The YL-like defect origin has been tentatively confirmed by comparing EL and photoluminescence (PL) results. To further explore the properties of YL-like EL centers, EL dependence on the drain-to-source and gate-to-source voltage were investigated. The direct comparison between the EL and temperature distribution images from the same GaN HEMT suggests that two distinct EL emission mechanisms exist at the off-state breakdown. The other type of EL emission at off-state is attributed to carrier intravalley transition due to hot carrier generation by impact ionization at localized breakdown sites. This type of hot carrier induced light emission was observed at on-state and off-state operations. The YL-like emission was shown to have a stronger electric field than the hot carrier induced emission. [DOI: 10.1143/JJAP.47.3336]

KEYWORDS: yellow luminescence, electroluminescence, GaN HEMT, electric field, temperature measurement

1. Introduction

Gallium nitride (GaN) is a promising material for optoelectronic and high power high-frequency electronic devices. However, defects induced by material growth and device fabrication can impose constraints on the device performance. The signature of yellow luminescence (YL) has been intensively studied using photoluminescence (PL) and cathodoluminescence (CL) methods as one of the most dominant deep level defects related to light emission. For GaN LEDs, yellow band EL has been observed both in forward and reverse biased conditions at room temperature.[1)] However, yellow band EL has only been observed in GaN high electron mobility transistors (HEMTs) at low temperature.[2)] Furthermore, the presence of YL-like defects has not been thoroughly investigated in HEMTs at room temperature. On the other hand, EL of the GaN HEMT has been intensively studied for EL induced by hot carrier generation and distribution. A unique one-peak EL spectrum profile from GaN HEMTs has been assigned to a possible origin of hot carrier induced intravalley transition,[3)] which is a different mechanism from other III–V compound semiconductor devices showing EL profiles of Maxwellian distribution.[4)] In this paper, we studied the light emission characteristics from GaN HEMTs. A yellow band EL characteristic, which might be attributed to the same origin as the YL defects, was observed at room temperature. In addition, a second EL peak from GaN HEMTs was tentatively assigned to the hot carrier induced intravalley transition peak. EL emission dependence on the drain-to-source and gate-to-source voltage was also investigated in both EL peaks, showing that a YL-like emission has a stronger electric field dependence than the hot carrier induced emission. To further explore the YL-like EL emission, besides investigating different EL images by changing the drain-to-source voltage and the gate-to-source voltage, we also performed additional experiments such as PL and temperature measurements on GaN HEMTs.

2. Device Fabrication

The AlGaN/GaN heterostructure was grown by metal organic chemical vapor deposition (MOCVD) on a SiC substrate. The device structure consists of a 0.1 µm AlN nucleation layer, a 1-µm-thick GaN buffer layer, and an undoped 250 Å $Al_{0.28}Ga_{0.72}N$ barrier layer. Two gate fingers with Pt/Au metal stack with a gate length of 0.2 µm were patterned by the electron beam lithography and followed by the plasma-enhanced CVD (PECVD) nitride passivation. The gate–source and gate–drain spacing were 1 µm. The threshold voltage was about −5 V. The maximum transconductance was 250 ms/mm and the maximum drain current was greater than 1 A/mm. The gate width of the device is 100 µm. The width of T-gate wing is 0.5 µm. The EL emission region is very close to the gate and between the gate and the drain so part of emission light may be covered by the gate wing.

3. Experiment and Results

To locate EL emission from HEMTs, we used a hyper-spectrum imaging (HPI) system,[4)] consisting of a microscope probe station with a high resolution liquid N_2 cooled charged-coupled device (CCD) camera, and an acousto-optic tunable filter (AOTF) as a band pass filter covering a wavelength ranging from 500 to 1000 nm. Our strategy to identify the defects was to bias the device at on-state (gate voltage higher than pinch-off voltage) and off-state (gate voltage much lower than pinch-off voltage) conditions so that light generation from solely hot electrons (on-state) can be differentiated from that producing from both electrons and holes (off-state breakdown). As shown in Figs. 1(a) and 1(b), the two-dimensional (2D) images of the on-state emission ($V_{GS} = -3$ V, $V_{DS} = 20$ V) and the off-state ($V_{GS} = -7$ V, $V_{DS} = 20$ V) were compared. Schematic cross section of the GaN HEMT along the z-axis in Fig. 1(a) is shown in Fig. 1(c). The light emission at on-state was continuous along the entire gate. When the gate was biased at off-state, light emission became discontinuous and had

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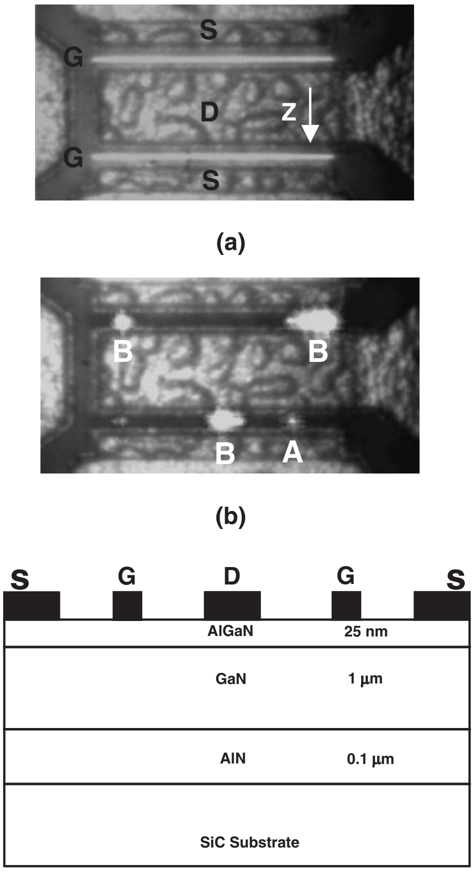
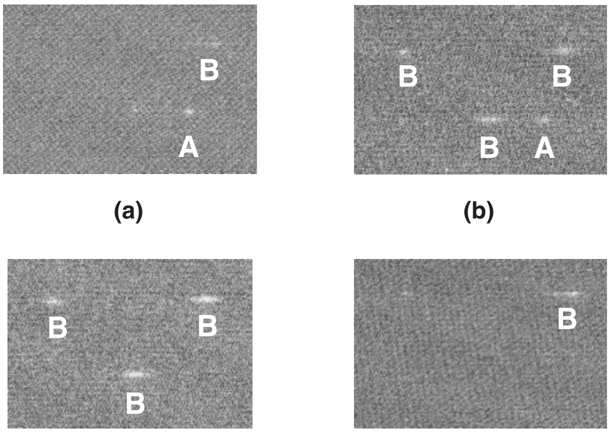


(a)

(b)

(c)

Fig. 1. (a) 2D image of on-state ($V_{GS} = -3$ V, $V_{DS} = 20$ V) electroluminescence overlapped with the device image, (S: source, D: drain, G: gate and *z*-axis). (b) 2D image of off-state electroluminescence ($V_{GS} = -7$ V, $V_{DS} = 20$ V) overlapped with the device image. The YL spot is labeled A and the hot carrier induced emission spot is labeled B in the images. (c) Schematic cross section of the GaN HEMT along the *z*-axis in (a). Figure not to scale.



(a) (b)

(c) (d)

Fig. 2. Two types of emission, YL-like spots and hot carrier induced emission spots observed at the wavelength of (a) 560, (b) 675, (c) 720, and (d) 900 nm. The YL spot is labeled A and the hot carrier induced emission spot is labeled B in the images.

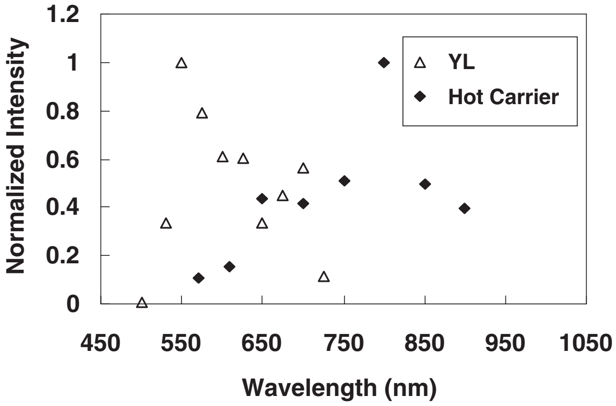


Fig. 3. Electroluminescence spectral profiles of YL-like spots and hot carrier induced emission spots at the off state ($V_{GS} = -7$ V, $V_{DS} = 20$ V).

several light spots. Most strikingly, those emission sites had two distinct features on the wavelength dependence. At the same bias condition as used in Fig. 1(b), 2D images could be viewed in different wavelengths with HPI system as shown in Fig. 2, The discrete point-like spot is labeled A and the other sites are labeled B in the images. At the filter wavelength of 550 nm, only the A spot could be seen clearly. As we increased the filter wavelength to 675 nm, both the A spot and the B sites showed up. As we further increased the filter wavelength to 720 nm, the A spot disappeared. Then, the B sites disappeared after we increased the filter wavelength to 900 nm. Figure 3 shows electroluminescence spectral profiles of the A and B spots at the off state ($V_{GS} = -7$ V, $V_{DS} = 20$ V). One type of the spots which we labeled the YL-like spot (A in the images) showed up in the yellow band wavelength and the other type which we labeled the hot carrier induced emission spot (B in the images) appeared in the longer wavelength. It is likely that the YL-like spot is associated with yellow luminescence defects which have been identified in CL, PL,[3,5)] and EL at low temperature[2)] in the GaN semiconductor devices.

To further confirm the YL-like defect origin of type A emission, we compared the EL and the PL measurements on an unbiased device on the same wafer. The PL measurement was conducted by having the unbiased device on the same wafer excited by 257 nm Argon laser and collecting the emission light by a CCD camera and a spectrometer. Besides a band-to-band emission peak around 370 nm, a YL peak around 600 nm was shown on the PL spectral profile. In the PL images, there were many visible PL spots distributed on the surface of the device similar to one previous report in GaN film.[6)] The spectral profile of those PL spots should correlate with the yellow PL spectrum because the band-to-band emission was out of the range of the CCD camera. Those yellow PL spots may be related to yellow EL as shown in Fig. 4, depicting the PL spectral profile pretty close to the EL's profile. On the other hand, the spectral profile of the type B emission spot is a single peak profile with a peak wavelength around 825 nm, which is similar to that reported in ref. 3 and explained as a signature of hot carrier induced intravalley transition.

To gain an in-depth understanding of the YL-like spot, we varied the V_{DS} and the V_{GS} while examining the EL intensity profiles along the gate width. With an increase of V_{GS} at a fixed $V_{DS} = 19$ V as shown in Fig. 5(a), the HEMT operated from off-state to on-state, which had plenty of hot electrons

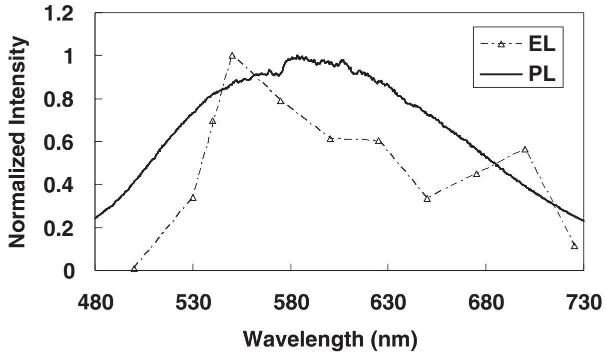


Fig. 4. Comparison of PL spectrum of an unbiased device on the same wafer and EL spectrum of the YL-like spot.

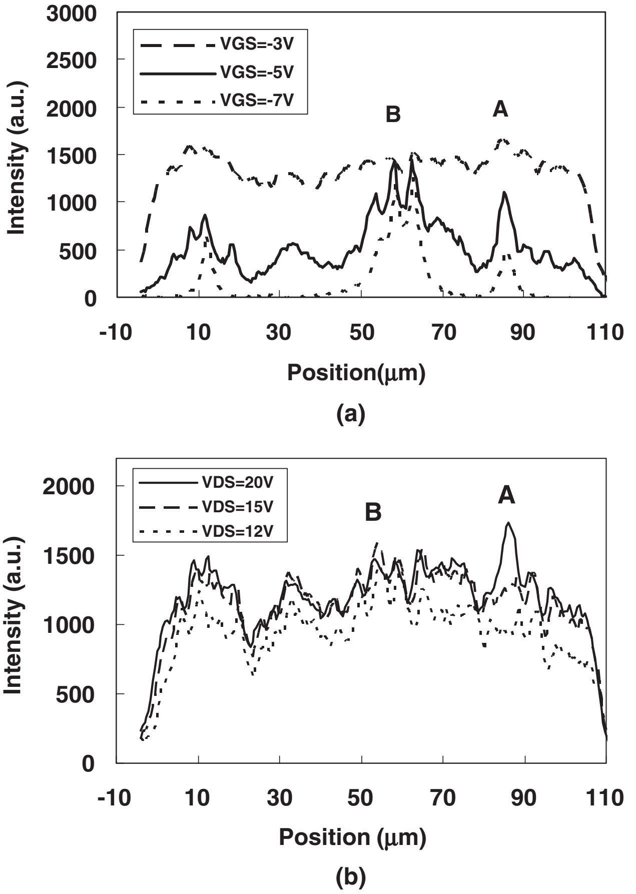


Fig. 5. EL intensity distribution along the lower gate width of the device at (a) various V_{GS} with fixed $V_{DS} = 19$ V (b) various V_{DS} with fixed $V_{GS} = -4$ V (on-state). The YL spot is labeled A and the hot carrier induced emission spot is labeled B in the figures.

to induce light emission and consequently masking the YL-like peak. This masking effect may be the reason that yellow EL could be observed with a spectrometer at low temperature but not at room temperature.[2] By changing the V_{DS} at $V_{GS} = -4$ V as shown in Fig. 5(b), the HEMT was operating at on-state but with different channel electric field. It showed most interestingly that the EL profiles depend on V_{DS} value. The YL-like peak as labeled was shown to have stronger electric field dependence on EL intensity than hot carrier induced emission. According to the previous reports, the YL PL is originated from defect complexes. These complexes form donor acceptor pairs such as V_{Ga}–O_N.[7,8] They are like dipoles. The dipoles as potential wells can hold or trap some electrons. When higher electric field is applied, the positive charge and the negative charge are stretched away. Electrons trapped by the potential wells can be released to enhance the YL-band transition. That might be attributed to a strong electric field dependence in this particular light emission spot.

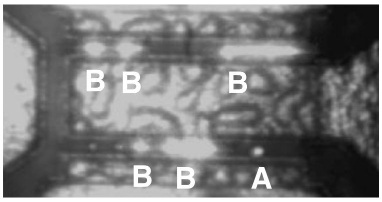


Fig. 6. 2D image of off-state EL ($V_{GS} = -7$ V, $V_{DS} = 20$ V) overlapped with the device image after off-state breakdown stress. The YL spot is labeled A and the hot carrier induced emission spot is labeled B in the images.

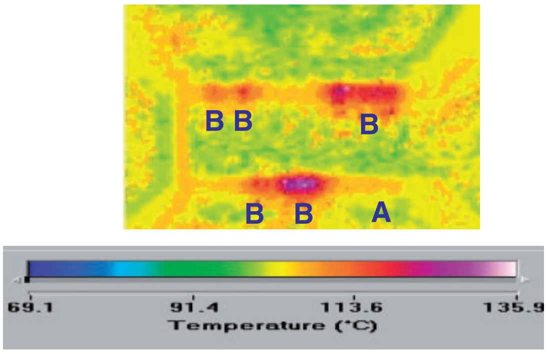


Fig. 7. 2D temperature profile of the device at off-state condition ($V_{GS} = -7$ V, $V_{DS} = 20$ V) after off-state breakdown stress. The YL spot is labeled A and the hot carrier induced emission spot is labeled B in the images.

Finally, we also biased the device for a period of time at the off-state breakdown condition as a means to induce device degradation by the hot carrier effect. The YL-like spot (type A emission) remained the same size while the hot carrier sites (type B emission) enlarged their coverage after stress as shown in Fig. 6 compared with the EL image before stress as shown in Fig. 1(b). Since the origin of YL is from some defect complexes, the atoms in defect complexes can not be altered due to the stress conditions. On the other hand, the increase of hot carrier emission region can be attributed to off-state current increase locally (i.e., more hot carriers locally) induced by the surface property at the passivation layer. To confirm the local current increase, a temperature distribution on the surface of the stressed device was measured as shown in Fig. 7. Note that the temperature is related to power dissipation, a product of the current and the bias voltage. While the hot carrier sites correlated with high temperature due to current flowing, the YL spot did not correlate with high temperature. The YL emission spot is due to the YL-band transition so that it does not correlate with high temperature observed in type B emission due to hot carriers.

4. Conclusions

We incorporated different techniques including EL measurements, PL measurements and temperature distribution along a gate finger to characterize the yellow EL and hot carrier EL in GaN HEMTs. The characteristics of the YL are similar to the yellow electroluminescence defect in GaN LEDs in reverse biased conditions. The YL-like defect origin has been tentatively confirmed by comparing EL and PL results and other properties. The YL-like defect spots have been found to be randomly distributed in HEMTs. All of the HEMT devices under this investigation show similar characteristics, some with multiple YL sites and others with none at all. The other type of emission at off-state is attributed to hot carrier induced light emission sites. This hot carrier induced light emission was also observed at on-state operations. The influences of YL-like and the hot carrier induced EL on electrical characteristics and performance of GaN HEMTs will be explored in the future.

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