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Optical investigation of degradation mechanisms in AlGaN/GaN high electron mobility transistors: Generation of non-radiative recombination centers

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Degradation mechanisms in AlGaN/GaN high electron mobility transistors have been studied under pinch-off conditions. Sites of localized emission of electroluminescence (EL) in the form of hotspots, known to be related to gate leakage currents, are shown to be the result of the generation of non-radiative recombination centers in the AlGaN device layer during device stress. EL from the hotspot site contains both hot-carrier emission from the acceleration of charge carriers in the device channel and defect-related transitions. Gate leakage through the generated centers is the most likely mechanism for the observation of EL hotspots. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3693427]

Because of their high power and high frequency performance, AlGaN/GaN high electron mobility transistors (HEMTs) offer great opportunities for next generation radiofrequency applications such as for communications and radars. However, AlGaN/GaN HEMTs still face reliability issues, which limit their lifetime. To reduce device degradation, it is essential to understand degradation mechanisms in detail; however, little is presently known about the physical nature of their degradation. Mechanisms such as the modification of pre-existing defects by hot carriers,[1] or in general hot-carrier effects,[2] have been suggested when devices are operated in the on state. In the off state, mechanisms such as diffusion and surface reactions, related in cases to pit formation, have been proposed.[3,4]

Electroluminescence (EL) has been used for AlGaN/GaN HEMTs operated in the on state to determine hot-electron temperature[5–8] and to probe changes in electric field distribution during stressing.[8] This hot-electron EL is caused by electrons, which have been accelerated within the device channel, scattering, and losing energy by emitting photons. It has been suggested[9] that excited electrons can have sufficient energy to occupy a higher valley within the conduction band before relaxing optically. Other features in the on state EL spectrum have been used to demonstrate the existence of impact ionization in AlGaN/GaN HEMTs.[10] In the off state EL has been used as an elegant tool to monitor device degradation in AlGaN/GaN HEMT devices. The often observed increase in gate leakage current, typically occurring above a critical voltage,[11] is correlated to the emergence on the drain side of the gate contact of EL emissions from localized spots in the off state.[12] The detailed origin of these hotspots, however, is presently not well known; proposed models include defects[13] and localized enhancements to the electric field.[9] In this letter, detailed optical spectroscopic analysis of EL hotspots, generated by device stress in the off state, combined with photoluminescence (PL) measurement, is used to illustrate the fact that the generation of hotspots is related to the generation of non-radiative defect states in the AlGaN device layer induced by device stress, leading to increased leakage currents in AlGaN/GaN HEMTs through the AlGaN device layer.

AlGaN/GaN HEMTs grown by plasma-assisted molecular beam epitaxy on a SiC substrate were studied; these consisted of 900 nm of GaN with a 30 nm $Al_{0.3}Ga_{0.7}N$ barrier. All devices studied had a gate width of 75 μm, a source-drain spacing of 5 μm, and a gate length of 1.5 μm. The devices were stressed in the off state up to $V_{DS} = 25$ V, with a negative voltage V_{GS} up to -16 V to produce device degradation. EL *images* were acquired from the devices using a Peltier-cooled camera with a response in the visible and near infrared spectral regions coupled to a microscope with a 0.75 numerical aperture (NA) objective, enabling an optical resolution of $\sim$0.7 μm. EL *spectroscopy* was performed using the same microscope in combination with a Renishaw spectrometer. PL spectroscopy on unbiased devices after off-state stress was performed using a frequency-doubled Argon-ion laser at 244 nm (5.08 eV), i.e., excitation above the AlGaN bandgap (4.07 eV) for these devices. A 0.5 NA objective (40×) was used to focus the laser light onto the device and to collect the PL signal. The PL spot size was $\sim$5 μm and the laser power incident on the sample was $\sim$0.2 mW.

Figure 1 shows the EL emission from a device after off-state stress. In the fresh device, no EL was observed in the off state. During stress, hotspots were observed to emerge on the drain side of the gate, increasing in density with stress time (Figures 1(a) and 1(b)), correlated to an increase in gate

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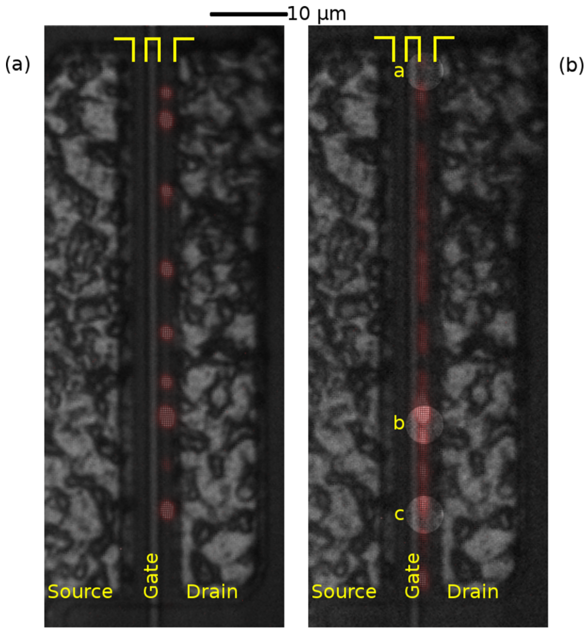

FIG. 1. (Color online) EL images overlaid on white-light images of an AlGaN/GaN HEMT (device 1) stressed at $V_{DS} = 25$ V, $V_{GS} = -16$ V for: (a) 30 min and (b) 80 h. Circles indicate the location and spatial resolution of subsequent 244 nm excitation PL measurements.

leakage current, as shown in the inset of Figure 2. EL spectra of representative hotspots are displayed in Figure 2. Clearly apparent is a dominant contribution in the red-infrared spectral range related to hot-carrier emission from carriers injected from the gate into the channel. In addition, enhanced emission in the visible spectral region (2-3 eV) is apparent, possibly related to yellow luminescence, i.e., defect-related optical transitions. The ripples visible in the tail of the off state spectrum are caused by Bragg interference effects due to reflections within the device. We note similar hotspot spectra were also recorded from metalorganic vapor phase epitaxy grown devices, in some cases the non-hot-carrier related feature could even take the form of a distinct peak at 2.8 eV, and in other cases there was no optical emission in this spectral range. For comparison, EL from the device operated in the on state is also shown in Figure 2. Only hot-carrier contributions to the EL are apparent, and no defect-related features can be seen. We note the on state spectrum shown was recorded before stress; spectra recorded after stress were similar with the intensity reduced slightly, as expected from previous work.[8] The tail of the spectrum is effectively dependent on the hot-carrier temperature (we note the on state spectrum shown was recorded before stress; spectra recorded after stress were similar with the intensity reduced slightly, as expected from previous work[8]).

In order to understand the origin of the EL hotspots, PL measurements were performed at sites in the devices where EL hotspots emerged during device stress, illustrated in Figure 3. Clearly apparent in the PL spectra are two features, one related to the GaN bandgap (3.4 eV) and one to the AlGaN bandgap (4.0 eV). A significant reduction of the AlGaN band edge PL compared to the GaN PL is apparent. This is also illustrated in Figure 4 showing a statistical analysis of a selection of hotspot locations, clearly showing that for each hotspot the AlGaN bandgap PL is reduced, with a greater reduction corresponding to a higher density of hotspots. With the diameter of the laser spot of ~5 μm being larger than the hotspots observed in EL, this illustrates that at the site of each individual hotspot the AlGaN PL must be reduced dramatically. We note that no significant reduction in the absolute GaN PL intensity was found, demonstrating that all changes take place in the AlGaN layer, during the device stress observed here.

As the 244 nm laser is absorbed in the AlGaN barrier and the top of the GaN buffer of the devices, any reduction in the AlGaN PL intensity in hotspot regions therefore indicates the generation of non-radiative recombination centers within the AlGaN barrier layer.

The emerging hotspots are related to leakage currents generated during device stress: Electrons are injected through the AlGaN barrier into the channel, where they are subsequently accelerated by the electric field along the device channel and flow to the drain. This is apparent in the

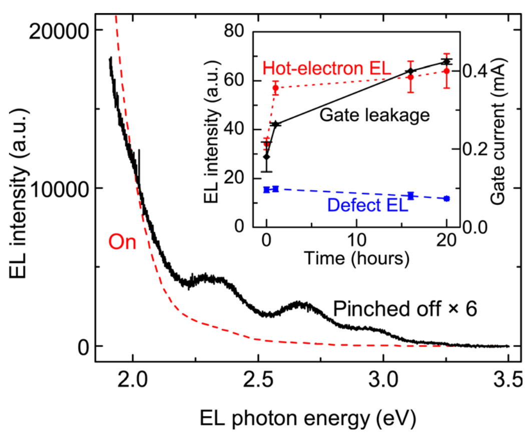

FIG. 2. (Color online) EL spectrum of a typical AlGaN/GaN HEMT device at $V_{DS} = 25$ V in off state ($V_{GS} = -16$ V, solid black line). For comparison an EL spectrum recorded in the on state is also shown ($V_{DS} = 25$ V, $V_{GS} = 0$ V, dashed red line). The ripples visible in the spectra are due to interference of light caused by internal reflections within the device (Bragg interference). Prior to the measurements the device was stressed for 17 h at $V_{DS} = 25$ V and V_{GS} up to -16 V. The inset shows hot-electron EL (red circles, 1.9-2.2 eV) and defect-related EL (blue squares, 2.8-3.1 eV) as a function of stress time, together with leakage current (black diamonds).

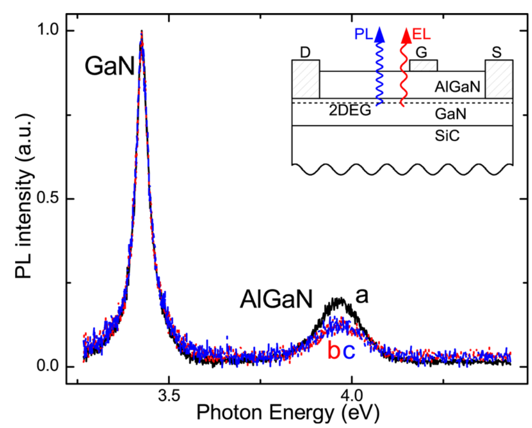

FIG. 3. (Color online) PL spectra from three regions of device 1: (a) without hotspots, (b), (c) with hotspots. The inset shows a cross-section of a typical HEMT and indicates schematically the areas where EL occurs and PL was recorded.

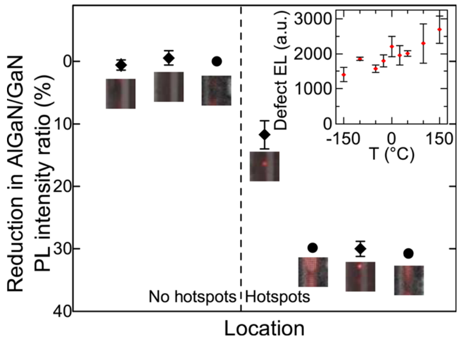

FIG. 4. (Color online) AlGaN to GaN PL intensity ratio (integrated peak area) recorded at selected locations along the gate edge of degraded devices, in regions with and without hotspots. EL images of the recorded areas are depicted. Inset shows the EL intensity in the 2.8–3.0 eV spectral range as a function of device temperature.

hot-carrier emission tail observed in the EL spectrum (Figure 2). Its intensity will be correlated to the gate leakage current through each particular hotspot, i.e., is a measure of the local leakage current, with the total leakage current being the integral over all hotspots. The gate current increases during device stress at constant bias as more leakage paths are formed. Under the stress conditions used for this work the drain current increased with the gate current; no increase in leakage from source to drain was observed, unlike in some step-stress measurements.[14] PL spectra showed the generation of defect states, namely, non-radiative recombination centers, only in the AlGaN barrier at the location of hotspots where leakage current occurs. This strongly suggests that these non-radiative recombination centers provide a percolative leakage pathway from the gate into the channel, as they do not occur outside the hotspot sites. This conclusion is consistent with the previously reported time-dependent generation of the leakage currents by Marcon *et al.*[15] Mechanisms that have been proposed for the generation of defect states during device stress include for example oxygen or carbon related centers,[3] but other centers may also be possible, such as dislocations[16] or defects generated by piezoelectric stress in the high-field region.[17,18] In either case a leakage current path analogous to the percolation paths found in the oxide layer under the gate of a Si metal-oxide-semiconductor field-effect transistor[15,19] can, therefore, also occur in AlGaN/GaN HEMTs during device stress as defects accumulate. These defects affect drain current reducing the output power.[3,20]

Once the carriers penetrate from the gate through the AlGaN barrier into the device channel, they are accelerated. Hot electron temperature was determined from the hot-carrier contribution to the EL spectrum. The hot electron temperature determined from the hotspots at for example $V_{DS} = 25$ V was 3100 K, which is higher than the hot electron temperature determined at the same source-drain bias in the on state (1800 K). This is expected as the field is higher in the off state under the same source-drain voltage but different gate bias. The defect-related features in the EL spectrum were found to be more or less constant during device stress, once hotspots were generated. The observed defect feature in the EL spectrum therefore seems not to be related to newly generated defects as, otherwise, an increasing intensity with increasing leakage current would be expected to occur. Instead they are likely due to pre-existing defects in the device layers, unaffected by the degradation processes. Features such as yellow luminescence (which has been attributed to Ga vacancies)[21] or shallow-donor deep-acceptor pair recombination in the GaN buffer[22] are known to occur in this spectral range and are likely contributors to this defect emission observed. The existence of these defect-related features in the EL spectrum requires holes to be present in the devices to recombine with the electrons injected from the gate into the buffer. This hole current can be estimated from the magnitude of the defect-related EL, taking into account the optical throughput of the spectrometer, in the range of 10^{-17}–10^{-16} A. If these holes are supplied by traps, freeze-out would be expected to reduce the defect-related EL emission at low temperatures, while impact ionization would lead to an increased hole supply at low temperatures due to an increased electron mean free path.[10] Figure 4 shows the behavior of this peak as a function of temperature. The decrease in EL intensity with decreasing temperature suggests that hole traps are the predominant source of holes for the devices considered here, although the detailed physical nature of these hole traps is not clear, considering their low density as demonstrated by the low hole current.

In conclusion, EL imaging and spectroscopy combined with PL spectroscopy was used to study device degradation of AlGaN/GaN HEMTs. The sites of EL hotspots generated during device stress, linked to the emergence of gate leakage current, are shown to be related to the generation of non-radiative recombination centers in the AlGaN device layer in AlGaN/GaN HEMTs, which provide a pathway for gate leakage to emerge. EL hotspots contained contributions from both hot-carrier emission and defect features, the latter relating to pre-existing defects.

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