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A study on the impact of mid-gap defects on vertical GaN diodes.

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***Abstract*- GaN is a favorable martial for future efficient high voltage power switches. GaN has not dominated the power electronics market due to immature substrate, homoepitaxial growth, and immature processing technology. Understanding the impact of the substrate and homoepitaxial growth on the device performance is crucial for boosting the performance of GaN. In this work, we studied vertical GaN PiN diodes that were fabricated on non-homogenous HVPE substrates from two different vendors. We show that defects that stemmed from growth techniques manifest themselves as leakage hubs. Different non-homogenous substrates showed different distribution of those defects spatially with the lesser quality substrates clustering those defects in clusters that causes pre-mature breakdown. Energetically these defects are mostly mid-gap around 1.8Ev with light emission spans from 450nm to 700nm. Photon emission spectrometry and hyperspectral electroluminescence were used to locate these defects spatially and energetically.**

Keywords: GaN, Hyperspectral Electroluminescence, Vertical Diode, Failure analysis, Characterization

I. INTRODUCTION

GaN offers advantages for high power and RF power application. GaN possess properties that are custom made to meet the high power demands. This uniqueness stems from its material properties such large band gap, high mobility, thermal conductivity, polarization induced carrier concentration[1], [2]. In the power switching applications reliability is the main hurdle that prevents GaN from prevailing [3]–[5]. Although much attention has focused on engineering the contact and the doping levels in GaN diodes to boost their drive current, and reduce the Ron [6], [7], less is understood about how to tune epitaxial growth and edge termination to improve the stability and reliability of these devices In this paper, we investigated for the first time a study on the impact of the non-homogenous substrates defects on the breakdown and reliability. Here, we show that two different vertical GaN structures that were built on non-homogenous substrates from different vendors exhibits high leakage current at lower than expected voltage[8], [9].

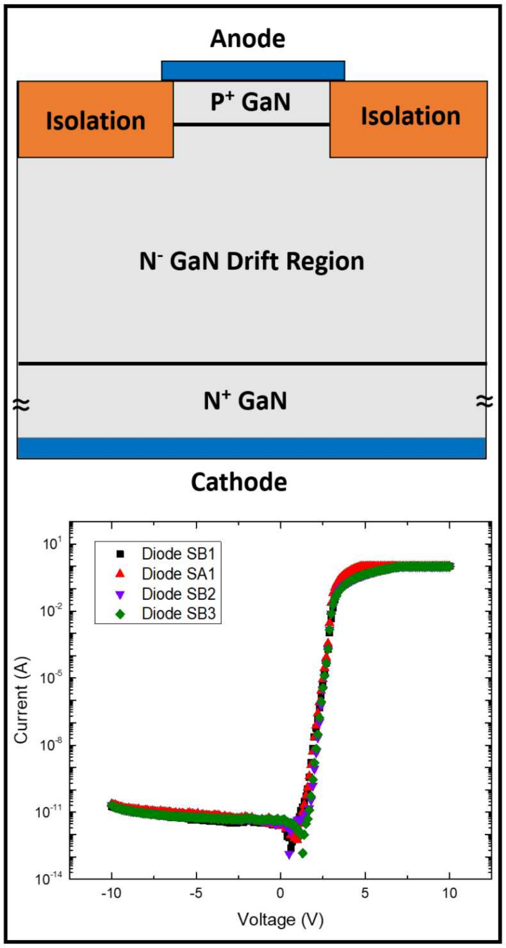

Figure 1: (Top) Schematic that represents our vertical PiN GaN diodes structure. (Bottom) I-V DC forward DC I-V sweep for all the devices in this work.

Furthermore, these devices demonstrate similar DC-IV characteristics. The only clue on the difference in their reverse bias performance was suggested from their spectroscopy emission under both the forward and reverse constant bias conditions. Further, we delve into the reverse

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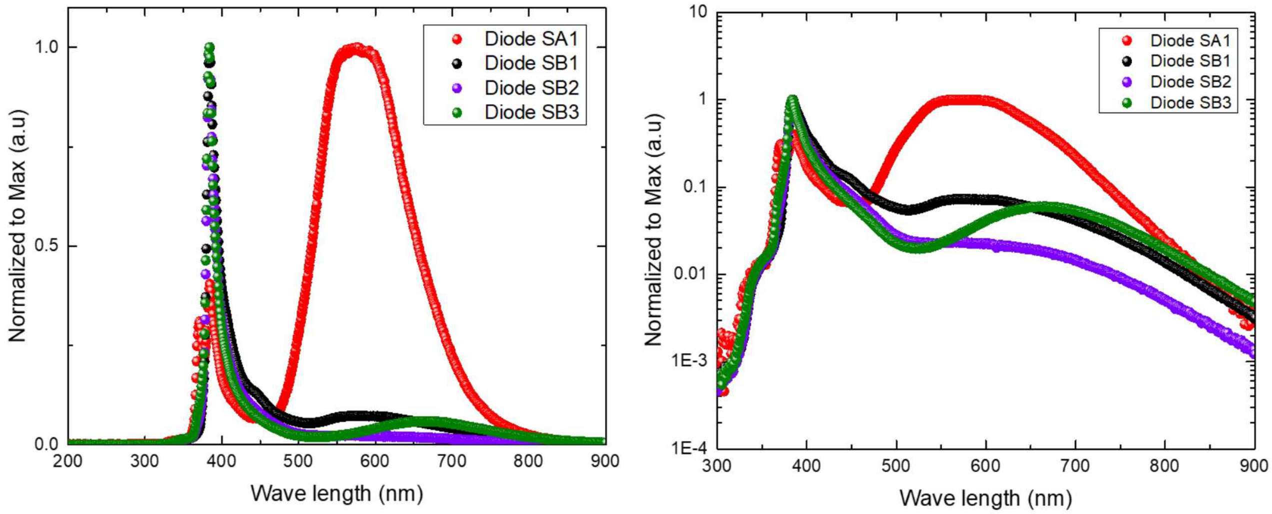


Figure 2: (left) Normalized to the maximum plot of the standard spectrometer spectra for the same devices under 0.9A forward current hold. (Right) logarithmic representation of the plot on the right to highlight the subtle difference among diodes from substrate B.

biased spectra using electroluminescence tool to isolate clusters of defects that are believed to be the failure points. This work is an extension of our previous work presented at the 2020 International Conference on Compound Semiconductor Manufacturing Technology[10].

II. EXPERIMENT

Starting with commercial non-homogenous GaN substrate, we grew MOCVD lightly doped layer of 8um with doping concentration of the order of 1-2E16 cm^{-3} followed by 500nm of Mg-doped layer with acceptor atoms count of $4E17cm^{-3}$ followed by a thin p++ Mg doped layer to facilitate the Ohmic contact [2]. The devices are fabricated following typical GaN PiN diode processes described elsewhere [11]. In this study, we investigated two non-homogenous substrates: substrate A (Sub-A) and substrate B (Sub-B) from two different vendors. Four vertical PiN diodes with similar structure are discussed in this paper. One diode was fabricated on Sub-A, while the other three diodes were fabricated on Sub-B. Figure 1 top shows a schematic cross-section that represents the vertical GaN diode structure on all devices. All four devices were measured under DC I-V sweep using Keithley 4200, Figure 1 bottom displays their forward DC I-V sweep that was taken at atmospheric environment.

A standard spectrometer was used to collect and analyze the luminescence during the forward bias hold. In this test an Ocean optics spectrometer was used to gather and analyze the photon emission under 0.9A forward bias for 10sec. The relatively high bias current was needed because the standard spectrometer setup was on a probe manipulator without an objective to guide the light thus a high current was needed to compensate for the loss in photons. The left plot in in Figure 2 depicts their spectra normalized to the max, while right plot was plotted with logarithmic scale to highlight the difference in the spectra of Sub-B devices. A more sophisticated apparatus can be implemented to collected the photons with minimum loss in the future. Nevertheless, the spectra reveal a significant difference between that devices that are otherwise similar.

To further investigate these conspicuous peaks, hyperspectral electroluminescence mapping was utilized to locate the photon emission areas on the device by imposing the emission location in pixels on the optical image taken by the same tool. The devices were tested in our custom made vacuum probe station coupled with a Photon, Etc. IMA-EL hyperspectral Imager that has 250-1000nm imaging range allows us to collect images with 2nm resolution. The use of vacuum environment presents an advantage over Fluorinert testing as it preserves optical access to the device for imaging under high voltage stress conditions. Broadband and a series of monochromatic images with 10nm step size were taken to enable pixel-by-pixel spectrum extraction at the forward bias of 0.1A and same acquisition time for all devices. The forward bias hyperspectral electroluminescence mapping of the device emission identifies the wavelengths of interest. Later, a reverse bias monochromatic electroluminescence images were taken on device SA1 at these wavelengths during high reverse voltage hold using Keithley 237.

III. RESULTS AND DISCUSSION

Though DC-IV forward sweep was nearly identical across the four devices there is a distinct difference amongst their photon emission depicted in figure 2. The forward I-V characteristics for devices SB2, SB3, SB1, &SA1 are plotted to absolute scale as both devices have the same device area. Figure 2 however needed to be normalized due to the difference in the absolute number of counts amongst the devices. The emission collection was taken under the same condition however, there was a noticeable difference in the number of counts that probably reflects the difference between the two substrate types. The wavelength emission around 379 nm is a result of the GaN which strongly relates bandgap emissions. Diode, SA1 from Sub-A has a high and broad peak that extend from 450nm to 700nm and is centered around ~660nm. This broad peak has a higher photon emission than the bandgap emission itself. the That broad peak is an agglomeration of multiple peaks that represent defects in the yellow and red bands in GaN. These defects are believed to relate to a convolution of Ga and N vacancies [12], [13]. Similar, but more discrete peaks appear in the other three devices but with a lower amplitude, in fact it is lower than the GaN band edge emission. This indicates some count of vacancies in sub-B, but the accumulative counts of them is far less than the one in device SA1 that was fabricated on Sub-A. Generally, the violet band emission from GaN bandgap is stronger in the devices from Sub-B. Furthermore, the conspicuous peaks between 450-700nm vary in their intensity across all devices. These wavelengths represent energy levels near mid-gap and deeper.

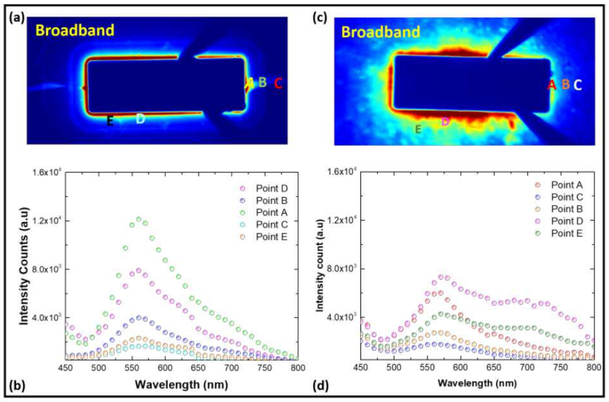
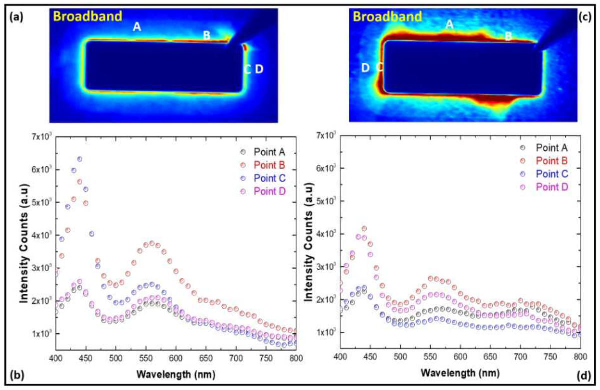


Figure 3: (a) Broadband image of diode SA1,(b) Hyperspectral Electroluminescence for several points on the same device. (c) Broadband image of diode SB1,(b) Hyperspectral Electroluminescence for several points on the same device.

To compare and investigate further the devices at the forward bias, a series of Electroluminescence hyperspectral images with 10nm step size were taken to enable pixel-by-pixel spectrum extraction at the forward bias of 0.1A and same acquisition time for all devices. The forward current was reduced to 0.1A to avoid saturating the cooled CCD detector. Figures 3 and 4 illustrates the broadband EL image, capturing all wavelengths, along with the extracted pixel intensity vs wavelength from the data cube. EL test was applied for all devices under the same biasing conditions. Each device has its own spectra plot along with broadband inset image of the devices. The spectrum was extracted from several points from the anode and outward the neighboring device. The emission spectrum is comparable among the three different devices from sub-B points, in some devices there is a presence of a broad peak in the red spectral region from 700-800 nm and a stronger peak in the yellow spectral region centered around 500-600 nm. The position of the broad peak shift across several points on each device, that is likely due to multiple peaks with different relative contributions varying spatially along the active area. Device SA1 from Sub-A has strongest intensity around the yellow band revealing mid-gap traps and defects, the peak is broad similar to the spectroscopy results in figure 2. These results confirm that non-homogenous substrates have common defects that have stemmed from the substrates. However sub-category of these non-homogenous substrates have clusters of those defects and these clusters of defects cause strong yellow band emission. These results raise the question on the impact of these defects and their distribution on the reverse performance, which is an important metric for power PiN diode.

It is worth mentioning that due to circumstances beyond our control, SB2 & SB3 have not been proceed for edge termination. Therefore, only devices SB1 & SA1 are considered in the reverse test because their edge-termination process have prepared them to manage relatively high electric field [11], [14]. The reverse DC I-V sweep mirrors the spectroscopy results. The device (SA1) that shows more peaks around the mid-gap have higher leakage which might lead to premature breakdown. Figure 5 displays the difference in the leakage current during a high reverse voltage sweep conducted on both SA1 and SB1. The reverse measurements were taken in a vacuum chamber. The leakage current is similar for voltage less than or equal to 400V, once that threshold is passed the leakage difference in diode SA1 becomes clearer. Several other devices on sub-A show that disparity in the leakage current beyond -400V. It is well known that threading dislocations that can extend through thick layers of MOCVD GaN and make some undesirable path ways to reverse currents [15]–[17]. Dislocations are distortions in the crystal structures that readily incorporate point defects such as vacancies and impurities at different energy levels. Though GaN native substrates provides a better seed to grow MOCVD GaN with low defectivity levels, non-homogenous substrates inherently exhibit regions with more defects and dislocations due to the manufacturing techniques. The substrate inhomogeneity leads to spatial variation in dislocation density, and impurity incorporation in the drift layer, which consequently impacts the electrical properties.



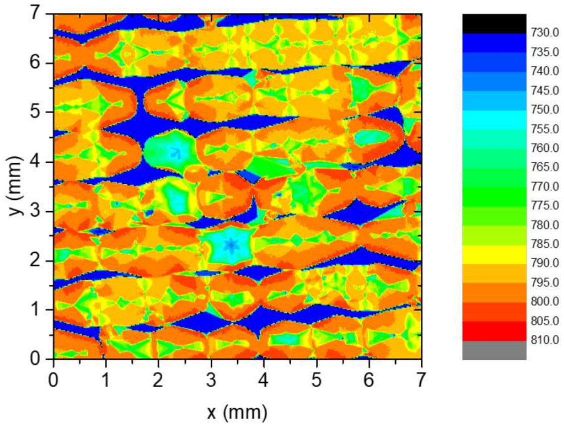


Figure 6: A_1 (LO) peak Raman Map on nonhomogeneous Substrate-A. The color distribution represents the peak position, which increases with carrier concentration.

Figure 4: (a) Broadband image of diode SB2,(b) Hyperspectral Electroluminescence for several points on the same device. (c) Broadband image of diode SB3,(b) Hyperspectral Electroluminescence for several points on the same device.

Raman mapping of the A1 (LO) peak has been shown to be a relevant technique for evaluating substrate uniformity [8]. As this peak is related to the donor concentration, it can reveal much about the carrier concentration across a wafer. The nonhomogeneous distribution of the carrier concentrations is strongly related to the extended defects as well as trap density across the region. Defects associated with yellow-band were shown to be related to interaction with trap donors. Figure 6 shows an example of A1 Raman map on nonhomogeneous substrate-A [8], [18].

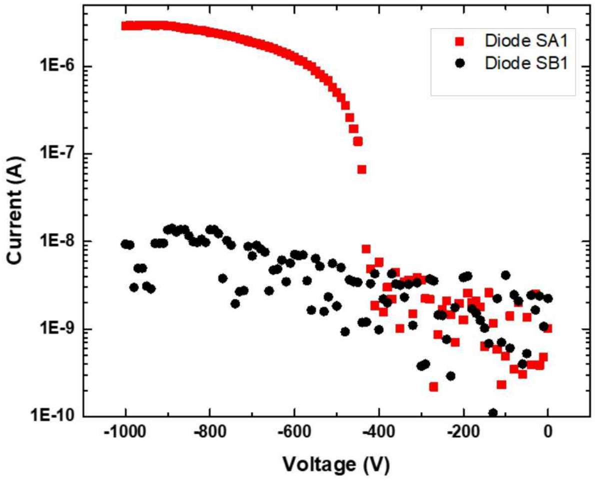


Figure 5: I-V Reverse Sweep in vacuum on both SB1 and SA1.

The broadening of the peak combined with the position shift results in three distinct regions: high carrier concentration (red), low carrier concentration (blue), and moderate one (green) [8]. It is important to appreciate that the Raman is only sensitive between 10^{17}-10^{18} cm^{-3} range. It is inevitable that the device active area spans cross regions. Thereby, it is not a surprise that device SA1 experiences much higher leakage current than device SB1 at the same reverse bias conditions.

To further investigate the reverse results presented in figure 5, electroluminescence monochromatic experiments was conducted. Device SB1 experiences three order of magnitude less leakage than device SA1. Therefore, device SB1 cannot be studied under these reverse conditions as the leakage current is too low resolve given the limitation of the 1.1kV voltage limit. Device SA1 on the other hand is a good candidate to study under reverse bias. Diodes, SB2 and SB3 has only isolation implants and the lack the termination ones thus isolated devices exhibited high leakage current at very low reverse voltage and not suitable for reverse bias study.

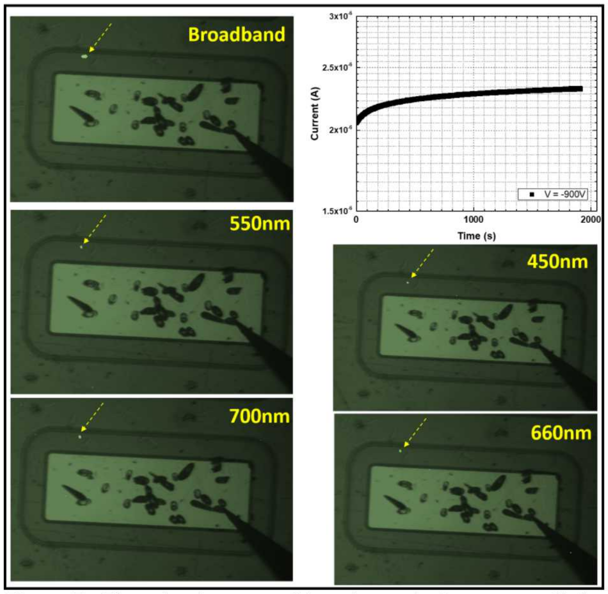


Figure 7: Electroluminescence Monochromatic images on diode SA1 during -900V reverse bias. Positional correlation between the leakage spots and their positions relative to the device. The leakage spots are observed at -900 V.

During the forward electroluminescence mapping of the device certain peaks have been identified and will be the focus during the reverse monochromatic electroluminescence. This experiment is held at ~100uA leakage current, it is important to monitor the leakage current throughout the experiment to make sure the leakage does not suddenly increase and the device enters breakdown regime. The stability of the current also guarantee the imaging quality thus no extra thermionic emission is distorting the images. Moreover, this experiment is taken at a constant voltage -900V and longer acquisition time per wave length is required due to low current density. Only few wave lengths were imaged to spatially locate the luminescence points on the device by imposing the emission location in pixel on the optical image taken by the same tool. Figure 7 captures the monochromatic electroluminescence results. The broad peak in the spectrometer in figure 2 and later in the hyperspectral luminescence translated to bright spots at 450, 550, 660 and 700nm respectively. These were the wavelengths investigated based on the forward hyperspectral results. The bright spots are a manifestation of current path during the reverse[19], [20]. The typical reserve current path is beneath the anode pad not few microns away from the pad towards the isolation trench. Sub-A displays a cluster of defects that facilitate the leakage path, those defects are distributed energetically and spatially [13], [21], [22]. Looking closer at the broadband image in figure 6 shows what it seems to be two bright spots close to the edge termination. In Figure 8 a lateral scan across the bright cluster shows that the bright spot in the broadband image is comprised from adjacent bright spots that originate from different energy levels. These adjacent points are unlikely caused by the fabrication process thus the analogous points around the device are not exhibiting the same level of emission. These are probably defects that stemmed from the substrate and are related to trap level near mid-gap [12], [13], [23].

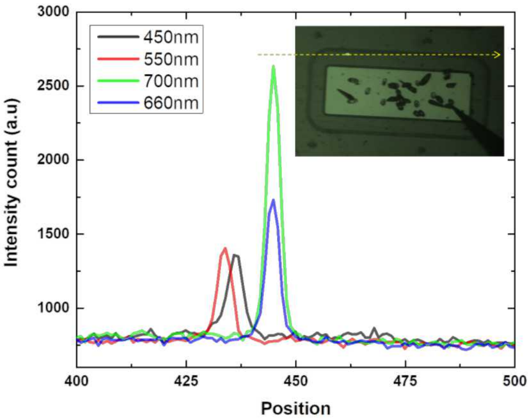


Figure 8: Lateral scan across diode SA1 show the peaks relative positon to each other.

IV. CONCLUSION

GaN is a thriving material for high voltage applications, sustaining a low leakage current during a reverse bias surge is a basic requirement for high-voltage diodes and arrestors. Reproducibility and reliability are important for GaN to thrive in the high power device realm. GaN native substrates are becoming the main stream in device fabrication due to the low defect density versus GaN on sapphire or Si []. Understanding the limitation of the common GaN on GaN technology by assessing the impact of the growth on the device especially in power application. In this work, we studied vertical GaN- PiN diodes that were fabricated on non-homogenous HVPE substrates from two different vendors. We showed that that non-homogenous substrates as a category have sub-categories. Substrate A where device SA1 is built on is an example of the sub-category in which many deep and mid-gap defects are clustered randomly across the wafer. SA1 displays quintessential performance that was observed on many other devices on the same substrate. Furthermore, the other nonhomogeneous substrate where the other three devices are fabricated on, represents a less defective category. The standard spectrometer identified potential performance issues that was not observed from the devices DC I-V forward characteristics. A hyperspectral electroluminescence imager was utilized to identify several troubling wavelengths of interest 450-700nm. These wavelengths were monochromatically scanned at a high reverse bias to spatially define the leakage spot and hence the potential failure point. The standard DV I-V sweep does not predict deficiencies that lead to high leakage current at high reverse biases. The devices emission resolved by Hyperspectral electroluminescence was a key in differentiating between the two substrates types. From the emission we identified defects around the yellow band which are a manifestation of gallium vacancies with substitutional oxygen impurities, that assesse the creation of hole-electron pairs [13], [23]. The future of GaN vertical devices relies on a deep understanding of the substrate, and epitaxial layers' impact on their stability at high voltages and currents. Our results indicate for the first time that these defects were spatially distributed and when they are in a close proximity they function as a leakage access point at the reverse bias which will directly impact the reliability. This technique can be applied to evaluate the impact of many process variations on device performance, including the introduction of regrown p-GaN layers, ion implantation and annealing for selective doping, and edge termination design. Finally, Photon emission spectrometer and hyperspectral electroluminescence were used to predict and locate these defects spatially and energetically. The standard photon emission spectrometer can be integrated in foundries production lines to assess devices without undergoing the high-voltage reverse test that usually require vacuum environment or Fluorinert.

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