The GaN(0001) yellow-luminescence-related surface state and its interaction with air

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ABSTRACT

Yellow luminescence (YL) is probably the longest and most studied defect-related luminescence band in GaN, yet its electronic structure or chemical identity remain unclear. Most of the theoretical work so far has attributed the feature to bulk defects, whereas spectroscopic studies have suggested a surface origin. Here, we apply deep level spectroscopy using sub-bandgap surface photovoltage that provides the energy distribution of the surface charge density. Comparison of surface charge spectra obtained under identical conditions before and after various surface treatments reveals the dynamics of the surface charge density. Further comparison with spectra of the entire state obtained using photoluminescence shows how the charge density stored in YL-related defects is eliminated upon a mild anneal in vacuum. This suggests that the YL-related defect involves a certain molecule adsorbed on the GaN surface, possibly in a complex with an intrinsic surface defect. The observed interaction with air strongly indicates that the YL-related deep level is a surface state.

1. Introduction

While Si technology has been departing from Moore's law, GaN has been emerging as the next technological semiconductor after silicon and has already secured its superiority in the niche of power electronics. Power electronics has been coming into focus with the advent of electric vehicles [1]. One of the major concerns in transistor semiconductors is crystal defects, and much research is naturally devoted to find ways to deactivate them. Defects have an undesired effect on device performance because they trap charge. Trapped charge affects the operational stability of GaN-based devices. Probably the best example for such instability is observed in AlGaN/GaN high electron mobility transistors (HEMT). AlGaN surface states and GaN bulk states are known to be the main source of current collapse and R_{DS-ON} issues during the transistor operation [2,3]. GaN light emitting diodes (LEDs), which made a revolution in the domestic lighting technology, are also vulnerable to presence of deep levels. Defect assisted generation, and charge trapping,

limit the injection efficiency of LED [4]. This emphasizes the role of defect characterization in further improvement of GaN-based devices.

Perhaps the most common of the GaN defects is the one associated with yellow luminescence (YL) [5]. Despite its limitations, photoluminescence (PL) has been the most common method in the study of semiconductor defects due to its ease of use and availability. An exceptionally wide sub-bandgap peak is often observed in PL spectra of GaN centered at ~2.2 eV. This wide peak is usually referred to as a "band" and has been dubbed the Yellow Band for its width and for the strong yellow emission often observable to the naked eye that governs the PL emission from GaN.

One of the intensive research debates regarding the YL has been the question whether it is a surface state or a bulk state. [6–25] The electronic device industry places particular value on the answer to this question, because surface states are accessible to surface treatments and hence may be more readily deactivated compared with their bulk counterparts.

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Over 1400 studies have been published on the origin of YL over the course of several decades. Theoretical ab-initio studies have been traditionally limited to bulk. Several such studies suggested the source to be Ga vacancies [6–8]. YL was also observed in p-type Mg-doped GaN and was also attributed to N-vacancies [9]. Van de Walle and Segev, presented an ab-initio model for surface state characterization and used it to study the surface of GaN [10]. Their results do not point to any YL-related state, and the model in general suggested similar energetic configuration for bulk and surface defects. In all, first principle calculations have not been able to define unambiguously whether the YL was a bulk or a surface defect. Experimental attempts to identify the exact location of the related defect have been numerous as well. In one of the earliest studies, Pankove and Hutchby studied PL in GaN that was ion implanted with 35 different elements, most of them induced a luminescence peak centered at ~2.15 eV [11]. While it seems likely that the damage of this implantation created additional Ga-vacancies in the bulk, the surface should have been damaged as well at the same time, thereby increasing the surface state density. Several studies suggested that a carbon impurity produces the YL [12–16].

Regardless of their exact energy distribution, it is widely accepted that c-plane-grown GaN has a high concentration of surface states [26]. Charge trapped in these states partially compensates the polarization charge. The result is upward band bending at both the Ga and the N faces of GaN, despite the opposite sign of their polar charges [27,28]. In GaN HEMTs, high density of surface states actually benefits the device as the source of the two-dimensional electron gas (2DEG) [29–31]. Several spectroscopic studies have shown a clear relation of the YL band to surface states. Based on cathodoluminescence (CL), an association of the YL to low angle grain boundaries containing dislocations has been suggested [17]. CL has also been used to show that a reaction of the GaN surface with Mg results in near surface electronic states [23], and to suggest a surface-related transition in GaN nanowires [24]. PL and surface photovoltage spectroscopy (SPS) identified the YL-related defect as a deep acceptor probably located at the surface [18]. A study of Pt/n-GaN Schottky barrier using internal photoemission spectroscopy showed photon-induced unpinning of the surface Fermi level with a substantial increase of the Schottky barrier height [25]. These results support the hypothesis of the YL surface origin. Based on PL, Hall effect, and deep level transient spectroscopy (DLTS) a transition from a shallow donor level to a deep level at Ev + 0.87 eV was suggested to underpin the YL emission [19]. While not specifically concerned with the question of surface vs. bulk origin, they did show that dry etch modified surface defects and increased the intensity of the yellow band, and suggested the formation of O_N (oxygen occupying a nitrogen site) complexes at the surface. A PL study of triangular cross-section GaN nanowires (NWs) showed that a feature at 2.26 eV was associated with surface states [20]. Attempts to identify the spatial location of the YL-related defect using photoluminescence excitation (PLE) spectroscopy showed controversial results. Hoffman et al. related the YL to the bulk defect located at 1.2 eV above the valence band [21], while Bouguerra et al. suggested that it is emitted from defects segregated near the surface or at other extended bulk defects [22]. Thus, while quite a few studies pointed to a surface origin of the YL, no clear-cut experimental evidence has been put forward as of yet.

The main concern for device performance is charge trapping by surface states. A useful technique for characterizing charge trapped in defects is surface photovoltage spectroscopy (SPS) [32]. Here, we use a charge characterization technique based on SPS to study the charge trapped at the surface of GaN. Our model provides qualitative energy distribution of the surface charge density over the GaN sub-bandgap energy range. We apply a series of different treatments to explore the dynamics of the surface charge distribution (occupancy) of the YL-related state. We show how this state (observed by PL) may be fully depleted of its charge (observed by SPS) using a mild thermal treatment in vacuum and then fully recharged on exposure to air.

2. Model

To obtain the spectrum of electrical charge from surface photovoltage spectra, one has to model the relation between them. This will eventually lead us to show that we have to take a photon-energy derivative of the surface photovoltage spectrum. The first attempts to use the photon-energy derivative of the photovoltage were made by Lagowski et al. [33] However, they have mistakenly assumed that the result of their model provided the dependence of the photoionization cross-section on the illumination photon energy [32]. Kronik et al. proposed a model suggesting that the energetic distribution of the surface charge can be obtained from the energy derivative of the square root of the photovoltage [34]. If the surface state distribution is fully occupied (charged), the distribution of surface charge and the distribution of the surface state are identical. However, as we will see here, surface treatments may change the charge distribution considerably, and therefore, to explore their effect, two methods are required. One, to observe the distribution of the state, and another, to observe the distribution of charge within this state. For the former, we use PL. For the latter, we use the SPS derivative. The model presented here uses a similar approach to obtain a qualitative energy distribution of the surface charge. In principle, the following model can provide a fully quantitative surface charge distribution. However, this would require the knowledge of several parameters, of which the precise experimental evaluation is relatively difficult. To support the conclusion that we propose here on the surface origin of the YL-related states, we believe a qualitative version of the model suffices, while a fully quantitative treatment may only add a marginal support, if at all, in disproportion to the required effort.

Without limiting the generality of the model, we will limit our discussion to n-type semiconductors. Abrupt termination of the semiconductor lattice, along with interaction of the surface with ambient substance may introduce allowed states within the forbidden gap. These states may either be vacant or occupied by charge carriers. The exact part of the surface states that is occupied (or charged) is defined by the Fermi-Dirac distribution. For simplicity, we will assume that all the states below the Fermi level energy are occupied by electrons, while those above it are vacant. Typically, the origin of the charge trapped in surface states is in electrons depleted from the bulk close to the semiconductor surface. This depletion results in an upward surface band bending in equilibrium. If, for example, one of these surface trapped electrons is excited using sufficiently energetic photon to be emitted over the surface barrier back into the bulk, the surface band bending will decrease (Fig. 1). It is difficult to evaluate the band bending without disturbing the equilibrium [35,36]. However, the change in the band bending caused by photo-excitation of charge over the surface barrier is readily evaluated by measuring the change in the contact potential difference, i.e. the surface photovoltage.

The density of bulk states, whether lattice imperfections or impurities, is generally lower by few orders of magnitude than the typical density of surface states. This is because the discontinuity of the lattice at the surface potentially provides a defect site per almost every surface atom. Moreover, not all bulk states affect the surface photovoltage, only those within the thin depletion layer. This further reduces their effect on the photovoltage as compared to that of surface states. [37]

The change in the surface band bending upon illumination, $\Delta V_{BB}(h\nu)$, caused by charge excitation over the surface barrier at a specific photon energy, $h\nu$, can be defined in terms of the Poisson equation:

$$V_{BBD} - \Delta V_{BB}(h\nu) = \frac{q}{2\varepsilon N_D}(N_{TD} - \Delta N_T(h\nu))^2 \qquad (1)$$

where V_{BBD} is the surface band bending at equilibrium (or in the dark), N_{TD} – the surface charge density at equilibrium, $\Delta N_T(h\nu)$ – the change in the surface charge, N_D – carrier (donor) concentration, q – electron

(a) Equilibrium

(b) Photovoltage

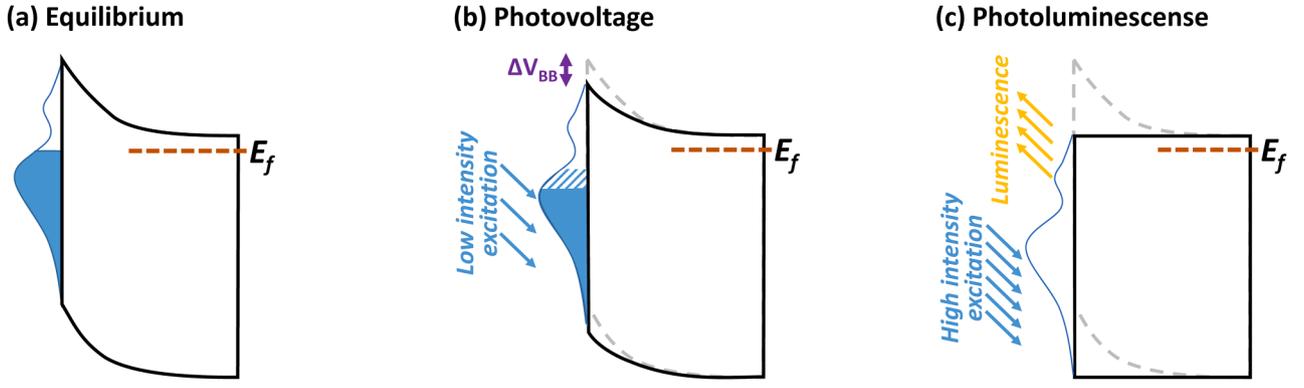

(c) Photoluminescense

Fig. 1. Cartoon showing band diagrams of a GaN sample (a) at equilibrium (in the dark), and during (b) SPS, and (c) PL acquisition. The low intensity excitation used in SPS partially depopulate electrons from originally occupied surface states, lowering the surface band bending, which is sensed as the measured photovoltage. In contrast, high intensity excitation during PL acquisition practically depletes all the surface states of their charge, resulting in approximately flat bands. Nonetheless, in both the SPS and the PL spectra the energetic position of all surface features relative to the conduction band minimum at the surface is maintained. Hence, the change in the band bending has no effect on the energetic position of the measured spectral features (except for minor shifts due to a second-order effects, as explained further). Comparing the distribution of the surface state (obtained from PL) with that of its charge (obtained from SPS), provides valuable insight into the dynamics of the surface state.

charge, and ε – dielectric constant. Taking the derivative of Eq (1) with respect to the photon energy, $h\nu$, yields:

$$\frac{d\Delta V_{BB}(h\nu)}{dh\nu} = \frac{q}{\varepsilon N_D}(N_{TD} - \Delta N_T(h\nu))\frac{d\Delta N_T(h\nu)}{dh\nu} \qquad (2)$$

Substitution of (1) into (2) yields the density of occupied states at a specific photon energy (or a specific surface energy with respect to the conduction band at the surface) $N_{OC}(h\nu)$.

$$N_{OC}(h\nu) = \frac{d\Delta N_T(h\nu)}{dh\nu} = \frac{c}{\sqrt{V_{BBD} - \Delta V_{BB}(h\nu)}}\frac{d\Delta V_{BB}(h\nu)}{dh\nu} \qquad (3)$$

This equation requires 2 parameters which in principle may be obtained experimentally: V_{BBD} and c. To obtain c, one has to measure the carrier concentration in the sample. However difficult, it should also be possible to obtain V_{BBD} experimentally and several methods have been previously proposed to that end [36]. We could also leave them as unknowns and evaluate their effect on the expected result. The term $\sqrt{V_{BBD} - \Delta V_{BB}(h\nu)}$ depends on the surface band bending in the dark (equilibrium band bending), which is unknown. However, we can approximate its value by illumination with high intensity and measuring the resulting photovoltage (the so-called photosaturation technique) [38]. The photon energy of the pumping beam should be high enough to excite the entire spectrum of surface states but lower than the band gap energy to prevent band-to-band excitation arising due to the Franz-Keldysh effect. Typically, a photon energy 200 meV below the band gap energy should suffice to prevent Franz-Keldysh excitation [39]. The resulting photovoltage may not equal the surface band bending in the dark, but should give a lower boundary of its value. If this result is significantly higher than the photovoltage values obtained by the illumination intensity used in our experiment, i.e. $\Delta V_{BB}(h\nu) \ll V_{BBD}$, we may assume the term $\sqrt{V_{BBD} - \Delta V_{BB}(h\nu)}$ to be constant, i.e. we assume a small perturbation regime. This also means that the photon flux used in our measurements does not excite the entire density of the surface charge but rather a small part of it. Therefore, to obtain the total density of the surface charge we should multiply our result by a constant factor, which represents the portion of the surface charge density that is excited by the photon flux used in our measurement. We now combine all these constants under C, which contains, among the elementary charge and material specific parameters from (1) and (2), the portion of the total charge excited by our illumination intensity. Assuming that this number remains constant throughout the entire spectrum we may define:

$$N_{OC}(h\nu) \approx C\frac{d\Delta V_{BB}(h\nu)}{dh\nu} \qquad (4)$$

Using Eq. (4), we can get a qualitative energy spectrum of the surface charge, which is relative to the actual value, even if its y-axis is not calibrated. Nonetheless, this suffices for our needs in the present study. Even if C does change mildly with the photon energy, it should be safe to assume that its variations are the same among several spectra acquired with the same setup on the same sample. We can thus quantitatively compare qualitative spectra obtained from the same specific sample under the same conditions but after different surface treatments.

3. Materials and methods

The GaN used in this study was a 2.2 um thick metal-organic vapor-phase epitaxy-grown n-type Ga-face GaN grown on c-plane sapphire and doped with both Si and Mg. The GaN samples did not undergo any surface preparation prior to their annealing in vacuum, and therefore, their surfaces should be regarded as "practical" rather than atomically clean. All measurements were carried out inside a stainless-steel vacuum chamber attached to a Janis ST-500 cryostat equipped with a heatable stage. To reduce the effect of noise on the derivative of the photovoltage spectra, we carried out the experiments on this temperature stabilized sample stage. The stage temperature was controlled using a Lake Shore 330 autotuning temperature controller and was set to 305 K in all measurements. Vacuum annealing was carried out on the same stage. We used a mild annealing temperature of 450 K in high vacuum (base pressure lower than 1×10^{-5} Torr) to avoid any major chemical changes and stay as much as possible away from lattice decomposition temperatures, while still being able to cause desorption.

Surface photovoltage was measured using a Kelvin probe (Besocke Delta Phi Gmbh). The sample was illuminated using a xenon light source monochromatized by a Newport MS257 spectrometer and filtered by order-sorting filters. At each wavelength step, the sample was illuminated for 5 min, at the end of which electrical measurements took place. The steps were equally spaced in energy (5 meV). At each point, the acquired value was obtained by averaging 100 consecutive measurements. The total time to acquire each spectrum was 33 hrs and it followed a relaxation period of 48 hrs in which the sample was kept in the dark in the Faraday cage chamber to make sure that the sample is at equilibrium before spectral acquisition commences. All the photovoltage spectra were obtained under a constant photon flux. The flux was maintained constant using an automatically-controlled slit at the light source. It is important to control the flux during the acquisition

rather than normalizing the spectra after the acquisition, because the latter method assumes that the optical response is linear with the light intensity while it is rarely so.

PL was excited using a 1 mW He-Cd laser (Meles-Griot Ltd.) lasing at 325 nm and acquired using a Newport MS257 spectrometer with a Si CCD detector.

4. Results and discussion

Fig. 2 shows a surface charge density profile calculated using Eq. (4). This profile was calculated from the measured photovoltage spectrum shown as an inset within the same figure. A charge distribution peak is observed over part of the YL band energy range, centered at around 2.08 eV. The distribution of charge may be different from the distribution of the state, because the state is not always charged in its entirety. For this reason, the charge density spectrum peaks at a slightly different energy than the typical PL spectrum.

Three SPS spectra were acquired from the same GaN sample at room temperature before and after the following treatments: (1) The sample was first measured in air, then (2) after evacuation of the measurement chamber to high vacuum, and (3) following a vacuum heat treatment at 450 K for 24 h and cooling down back to room temperature. Surface charge distribution spectra were then calculated from these photovoltage spectra using Eq. (4) and are shown in Fig. 3.

The charge spectrum obtained from GaN in air has two distinct features: a sharp peak centered at 2.08 eV (YL) and another wide peak at 2.77 eV (blue luminescence - BL). The magnitude of the YL peak decreases when measured after the evacuation of the chamber, while the BL peak remains unchanged. Following the anneal at 450 K the YL peak is entirely absent from the spectrum, while the BL increases its magnitude. These results suggest that the origin of the YL-related charge is probably in a certain surface adsorbate on the GaN surface, which gradually desorbed during the experiment. Evacuation of the sample environment seems to cause only limited desorption of molecules that are weakly attached to the surface, while anneal at 450 K desorbs all the remains of this adsorbate. Interestingly, this process was found to be fully reversible. Exposure of the sample to air restored the charge density spectrum to its original distribution, including the YL-related feature. This cycle was reproduced 3 times.

The shape of the BL remains unchanged in the first two spectra and increases in magnitude after the mild anneal. This suggests that its origin is probably not in weakly adsorbed molecules. While it may be a bulk
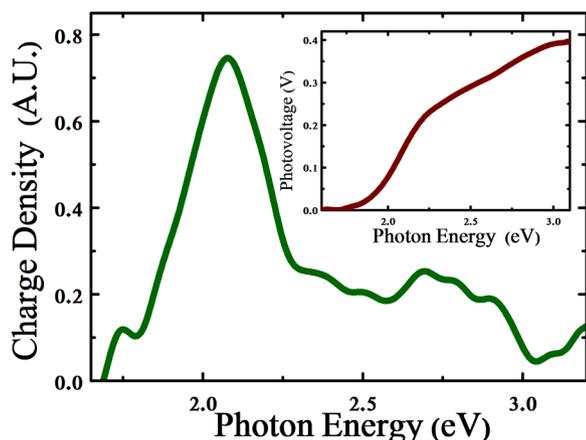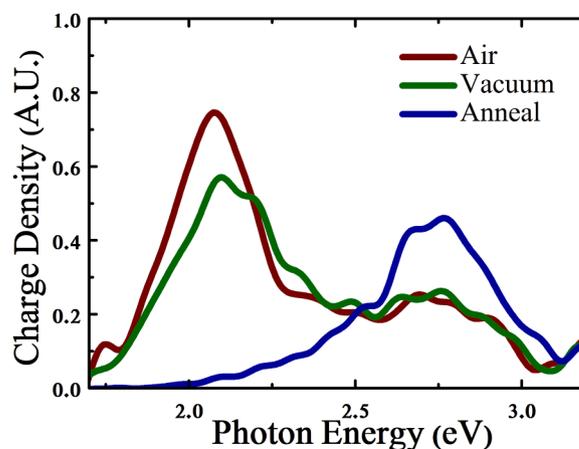

Fig. 3. Surface charge density obtained from same GaN sample at room temperature: in air (red), in vacuum (green), and after heating up to 450 K for 24 h in vacuum (blue).

state, it may also be a surface state that is not affected by our treatments. In fact, a spectral feature in this exact range has been previously attributed to surface oxidation of GaN [40]. Oxidation is a chemical process, whose product may require much higher energy to be removed, much greater than could be provided by the mild anneal used here. While we cannot conclude about its origin, the BL appears to be an independent spectral feature located at energies higher than the YL. Therefore, its presence has no bearing on the conclusions we wish to draw regarding the origin of the YL.

The reason for the increase in the BL magnitude after the anneal appears to be technical. We compare different spectra under the assumption that the band bending in the dark does not change significantly with our surface treatments. However, a complete elimination of the YL charge, which by rough estimate makes up at least half of the total surface charge density, if not more, must introduce a significant change to the surface band bending in the dark. If this change is not properly factored in, it might introduce an error in the form of an increase of the peak magnitude.

The SPS results of this study suggest that the charge stored in the YL-related state is removed upon a mild anneal in vacuum and restored after exposure to air. This does not necessarily imply that the YL-related state desorbs entirely. This is because SPS can only sense the surface charge and thus can give the distribution of the charged states only. To sense all the surface states, whether or not occupied, we use PL. We, therefore, acquired PL spectra from same GaN sample under the exact same conditions of the SPS experiment: in air, in vacuum, and after anneal in vacuum at 450 K for 24 hrs followed by cooling down to RT. The PL spectra (Fig. 4) show a practically unchanged magnitude of the YL peak, suggesting that the defect associated with this spectral feature is not desorbed. This important observation suggests that only the charge associated with the YL-related defect comes from an air-constituent molecule. This molecule adsorbs onto the surface state in air and desorbs by the vacuum anneal.

Comparing the YL-related peaks obtained from PL and SPS, it is evident that the latter is narrower and appears slightly shifted to a lower photon energy than the former. Narrower energy distribution of the charge distribution (SPS) compared to the surface state distribution (PL) indicates that the related state is only partially occupied. Whereas the shift of the surface charge distribution to lower energy appears to be due to the presence of the surface band bending barrier during the photovoltage acquisition. In the PL measurement, the high power of the exciting laser beam practically flattens the bands at the surface while strongly evacuating the state of its charge (Fig. 1c). Therefore, the PL spectrum provides the actual energy distribution of the surface state [31]. However, in SPS, the small perturbation regime leaves in place a
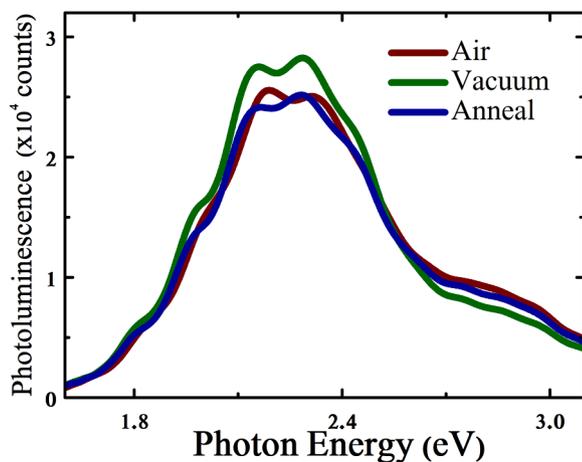

Fig. 2. Surface charge density obtained using Eq. (4) from the photovoltage spectrum shown as inset. For clarity, absolute values of both plots are shown. This exemplifies the use of the model presented here to obtain a qualitative charge density spectrum. The model assumes that the photovoltage is caused by surface states. The validity of this assumption for the YL-related state is established in the following a experiment.

Fig. 4. Photoluminescence spectra of the GaN in air, in vacuum and after anneal in vacuum at 450 K for 24 h. No significant change is observed after the various treatments, suggesting that the YL-related state does not desorbs, only the charge associated with it.

significant surface band bending. Electrons surpass this band-bending barrier mostly by internal photoemission. However, the built-in electric field within the band-bending region gives rise to a certain level of field emission through the barrier, i.e. field-assisted absorption, also known as the Franz-Keldysh effect [39]. This way some electrons traverse the barrier at less than its full height, thereby red-shifting the resulting charge spectrum (to a degree that is dependent on the field strength).

Comparing PL and SPS, we have been assuming that the deep levels related to the emission (PL) and the absorption (SPS) are spread over the same energies of the peaks. However, excited charge carriers may redistribute causing a shift of energy between absorption and emission, as in e.g., a Stokes shift [41]. A redistribution of charge requires that the charges thermalize – dissipate some of their energy due to phonon scattering. The latter process requires a continuum of allowed states over a range of energies. Hence, in a Stokes shift, the thermalization typically takes place within a band of allowed states, e.g., a conduction band. Once the charge has thermalized to the bottom of the band and reached the forbidden gap, the thermalization typically ceases due to the abrupt termination of the continuum and the absence of additional allowed states within the forbidden gap. Redistribution of charge within the forbidden gap is rarely reported, because in principle, it is forbidden. There is, of course, an exception to this rule – if the density of deep levels within the forbidden gap is high enough to form a continuum of allowed states [42,43]. A redistribution of charge within the forbidden gap was reported, for example, in amorphous Si. [44] The YL has often been called "the YL band" because of the extreme width of the observed luminescence peak that ranges over ~1 eV [45]. However, the density of its states appears to be far enough below degeneracy to support thermalization within this "band" [46]. The extremely large width of the YL peak clearly rules out this possibility. If the YL were a continuous band, PL would only show a narrow peak at the minimal transition energy, while the rest of its distribution would be filled through thermalization. For example, band-to-band emission transitions are always very narrow compared to those involving deep levels.

The present results may answer the long-persisting question regarding the location of the YL-related state. In general, YL can be associated with two different locations within the layer: in the bulk, or on the surface. The removal of the YL-related feature from the charge density spectrum after a mild anneal and its restoration on exposure to air present a clear scenario of interaction with the environment. A deep level situated in the bulk cannot interact with the environment without significant outdiffusion. Since outdiffusion is not possible at the low anneal temperature used here, the only possible configuration that

supports interaction with the environment requires that the deep level will be situated at the border with the environment, i.e., at the very surface. This study thus provides the most direct experimental evidence so far that the YL-related state is a surface state.

In fact, semiconductor free surfaces have long been known to interact with ambient gasses. Chakrapani has shown that when ambient O_2 and H_2O are adsorbed on surfaces of various semiconductors, they may act as a deep acceptor leading to the formation of a surface depletion region [47]. GaN makes no exception, and several adsorption studies have also been carried out on GaN surfaces. Based on first principle calculations, Rapcewicz et al. suggested that the large electronegativity of N in GaN provides adsorption sites at the GaN surface [48]. In their paper, they also showed that adsorption of hydrogen on the GaN surface, regardless of the surface polarity, stabilized the surface morphology. Hydrogen adsorption on the GaN surface was later confirmed by Bellitto et al. [49]. On the other hand, Bermudez has shown experimental evidence that oxygen can be chemisorbed on the GaN surface [50]. Adsorption of oxygen resulting in oxidation of GaN surface was reported as well [51, 52]. However, this mechanism cannot explain the reproducible/reversible adsorption/desorption behavior observed in our experiment. Dissociation of the GaN surface-formed Ga_2O_3 typically requires annealing at temperatures much higher than that which we used in this study [53,54]. Adsorption of another common air constituent, water, was reported in several studies. [55,56] Bermudez et Long used synchrotron ultraviolet photoemission spectroscopy (UPS) to show that water molecules dissociatively-adsorbed onto the GaN surface as OH [55]. Further annealing at 200 °C resulted in decomposition of the OH to adsorbed O and probably H. Interestingly, they also showed that the surface photovoltage-induced reduction in the band bending, an undesired secondary effect that typically accompanies the UPS acquisition, is greater on water-adsorbed surfaces. However, the authors did not address the effect of water adsorption on the YL-related state. Multiple other studies have also reported adsorption of various materials on GaN [57–64]. However, none of them reported any relation between the adsorption and the YL-related state.

Of particular relevance are studies that investigated the effect of the GaN surface adsorption on the surface photovoltage (SPV). Foussekis et al. used SPS to study the effect of UV illumination on the surface band bending of GaN under various ambient conditions [65]. They showed that UV illumination of air exposed GaN induced chemisorption of a certain substance on its surface, while illumination of the same sample in vacuum caused desorption of the adsorbates from the surface. Repeating the same experiment in dry nitrogen and oxygen, instead of air, they suggested that the adsorbate responsible for the reported behavior was oxygen. Another study from the same research team analyzed the rate of change of the SPV after turning off the illumination under various illumination intensities and sample temperatures [37]. They observed two distinct rates of relaxation: slow and fast. While the fast response was explained by classical recombination over the surface barrier, the slow response was attributed to chemisorption of oxygen on the thin surface oxide layer during illumination followed by desorption, after the light was switched off. However, both studies did not provide information on the energetic configuration of the surface states involved in the photo-adsorption process.

In summary, a large number of theoretical and experimental studies confirmed that GaN surfaces readily adsorb various constituents of air. This adsorption affected the charge population on the GaN surface, and the effect was observed as a change in the surface band bending. However, none of these studies correlated their observed change in the surface charge with any specific surface state. The adsorption-associated charging of the YL-related state observed in our study, testifies to the surface origin of this state, and associates it with an adsorption of an external species on the GaN surface. The air molecule that interacts with the YL-related surface state has yet to be identified.

5. Conclusion

Our results reveal the power of a combined method for observing deep level spectra (by PL) and the distribution of their charge (by SPS). Exploring deep level charge dynamics in response to a surface treatment, we show that the YL-related state may be depleted of its charge by a mild anneal in vacuum and then fully restored to its initial distribution by exposure to air. The conclusions that emerge seem to be compatible only with the premise that the GaN YL-related deep level is a surface state that interacts with airborne molecules. These results are important news for the GaN device community, because a surface state is accessible to surface treatments and may be removed or passivated. This surface charge may be responsible for some of the instabilities observed in GaN devices and our findings can pave the way to its prevention or deactivation.

Declaration of Competing Interest

This work has not been published anywhere and is not under consideration for publication with another journal. All authors aware of, and have agreed with this submission. We declare no conflict of interest.

Data availability

Data will be made available on request.

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