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The Radial Effect for E1 and E3 Deep Traps Concentration in n-GaN Layers

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In this paper, we report on the electrical properties of two commonly observed deep levels in n-GaN known as E1 ($E_c = 0.25$ eV) and E3 center ($E_c = 0.55$–0.6 eV). The defects analysis has been carried out with the use of deep level transient spectroscopy and Laplace deep level transient spectroscopy techniques, respectively. We have found that both E1 and E3 trap concentration strongly depends on the distance to the original wafer edge, which is called here the radial effect, and decreases by over two orders of magnitudes as the distance increases. Moreover, we speculate that both deep levels can be related to iron or its complexes.

topics: GaN, Fe, Iron, deep level transient spectroscopy (DLTS)

1. Introduction

Due to its superior properties, gallium nitride (GaN) is a very promising material for a wide range of applications such as blue laser diodes, light-emitting diodes (LEDs), or high electron mobility transistors (HEMTs) [1–3]. The potential of GaN-based materials in such applications as electronics and opto-electronics is well known, however, the technology of GaN and other nitrides growth is far from trivial. Thus crystal defects are present in GaN as well, but their origin has not been fully understood so far. As an example, one can recall E1 and E3 deep levels in GaN, which are always present in lightly doped GaN layers, no matter the growth method [4–6]. Despite numerous publications in the field and years of experimental and theoretical research on GaN-based materials, the origin of both traps is still controversial.

Deep level transient spectroscopy (DLTS) is an experimental technique that has been successfully used to study properties of deep levels in semiconductors for over 50 years since the first DLTS spectrum was shown by David Lang [7]. The technique is based on monitoring the capacitance transient due to carrier emission from a deep level present in the space charge region of the Schottky diode or p–n junction and defects parameters, such as activation energy (Ea), concentration of which (N_T) can be easily obtained.

In the present paper, we report on the results of the measurements carried out on n-GaN:Si Schottky diodes with the use of DLTS. DLTS measurements revealed two signals, the density of which strongly correlates with the distance to the wafer edge. Moreover, we suggest that both defects can be related to iron or its complexes.

2. Experiment

A highly doped 400 nm thick n+GaN layer, Si-doped to a nominal value of about 2×10^{18} cm^{-3}, was grown by metal-organic vapor-phase epitaxy (MOVPE) technique on a highly conductive n-type ammono-GaN substrate [8]. Silicon doped 100 nm thick n-GaN (5×10^{17} cm^{-3}) was grown, followed by a 1.5 μm thick n-GaN drift layer with effective donor concentration ($N_D - N_A$) close to 2×10^{16} cm^{-3}. Next, the structure was processed to thermally evaporated Ni/Au Schottky diodes deposited on top of the structure (on the n-GaN surface) with a diode area of 0.5 mm^2. Schottky Barrier diodes (SBDs) were fabricated in the form of an array of 72 diodes.

Prior to Schottky contact deposition, Ti/Al/Ni/Au ohmic contacts were fabricated on the back side of the structure and sintered at 850°C for 1 min in an N_2 atmosphere. More details on Schottky diodes processing can be found in [9].

DLTS measurements have been carried out within the temperature range from 77 to 500 K with an average rate of 3 K/min. Laplace DLTS [10] have been used to estimate total E3 trap amplitude only at 300 K. Capacitance transients were captured using Boonton 72B capacitance meter (1 MHz) and then analyzed by AD/DA acquisition card and software controlled by a computer.

3. Results and discussion

The diodes parameters such as ideality factor ($n \simeq 1.05$), series resistance ($R_s = 3.5\ \Omega$), barrier height (0.9 eV), and leakage current ($I < 10^{-8}$ at -10 V) were evaluated from current–voltage (I–V) measurements (not shown here). Extracted parameters confirm the high quality of the material, as well as Schottky diodes processing. In turn, the capacitance–voltage (C–V) measurements confirmed uniform doping of the drift layer and net donor concentration of 1.8×10^{16} cm^{-3} at 300 K and only slightly lower at 80 K (see Fig. 1).

In Fig. 2, three conventional DLTS spectra measured for diodes located close (red), medium (green), and far (blue) from the original wafer edge are shown for comparison. The measurements were performed at the reverse bias equal to -5 V, the rate window equal to 50 Hz, and 0 V filling pulse height. The width of the pulse was fixed to 1 ms.

In our sample, three strong peaks related to deep traps were detected by the DLTS technique. The first signal appears at 150 K (trap 1), the second around 310 K (trap 2), and the last close to 420–450 K (trap 3), respectively. As one can see in Fig. 2, high temperature signal amplitude seems to be almost constant, while two others are inversely correlated with diode-to-edge distance. Here, diode-to-edge distance stands for a horizontal distance between individual SBDs deposited on the n-GaN surface and sample edge. Further DLTS analysis revealed that a high temperature signal is present in the sub-surface region only ($x_d < 300$ nm) and is introduced into the material during the diode processing rather than during the structure growth. Thus it will not be considered in this paper anymore. In contrast, two other and more prominent DLTS signals are present in the whole space charge region, including the sub-surface and bulk region.

Finally, DLTS spectra plotted in Fig. 2 show a very strong dependence of trap 1 and trap 2 amplitude on the diode-to-edge distance. DLTS signal

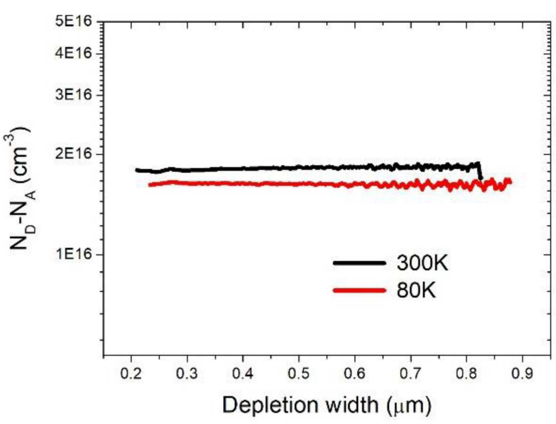

Fig. 1. Net donor concentration for studied n-GaN:Si layers obtained from C–V measurement with a probing frequency of 1 MHz.

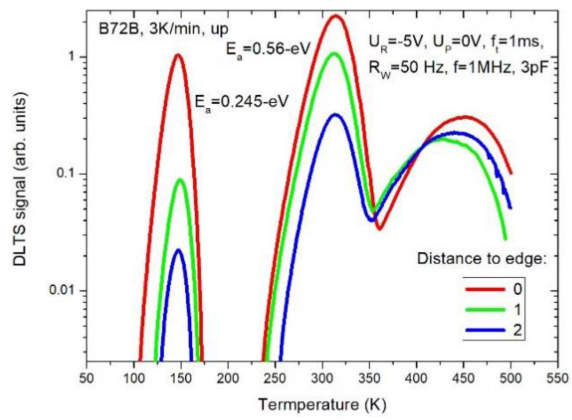

Fig. 2. Typical DLTS spectra measured for three Schottky diodes as a function of diode-to-edge distance.

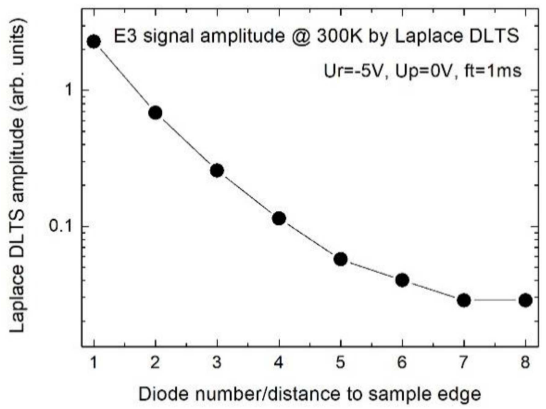

Fig. 3. E3 signal amplitude at 300 K measured by Laplace DLTS as a function of diode-to-edge distance.

decreases almost one order of magnitude for trap 2, while a signal drop as high as two orders of magnitude takes place for the T1 state. It is necessary to mention that DLTS spectra shown in Fig. 2 correspond to diode-to-edge distances equal to 1, 2.1, and 3.2 mm, which are labelled as 0, 1, and 2 in Fig. 2, respectively.

DLTS scans taken for SBDs diodes located much further from the wafer edge showed that trap 1 concentration does not decrease anymore while the DLTS signal for trap 2 decreases gradually across the next 3–4 mm and finally saturates on the same level as for trap 1. The trap 2 amplitude decrease measured by the Laplace DLTS technique at 300 K as a function of diode-to-edge distance is shown in Fig. 3. The rapid signal decreases described above, we call here a *radial effect*. However, this effect is limited to a very small portion of the structure close to the wafer edge only.

Since DLTS amplitude is directly proportional to the defect concentration, it is clear that both traps are non-uniformly distributed across the wafer with much higher traps concentrations close to the edge

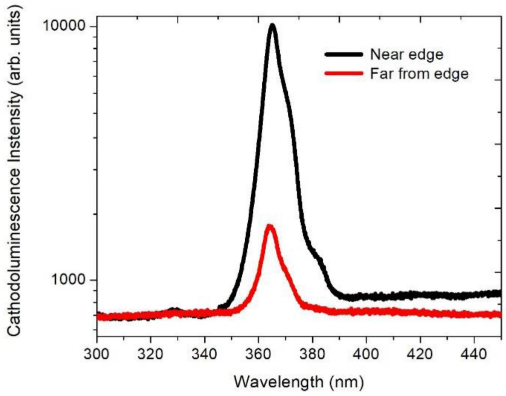

Fig. 4. CL data taken at 300 K ($U = 10$ kV, $I = 1.55$ nA) in region close and far to the sample edge.

($N_T \simeq 10^{14}$ cm^{-3}) and lower in other parts of the structure ($N_T \simeq 4 \times 10^{12}$ cm^{-3}). Moreover, a simultaneous decrease of both DLTS amplitudes can suggest common defects origin that was never reported before.

Cathodoluminescence (CL) results measured at 300 K (Fig. 4) also showed radiative recombination inhomogeneity across the wafer resulting in a 5 times higher intensity of band-to-band transition in regions close to the sample edge. Monte Carlo simulations confirmed that the CL signal was collected from the n-GaN layer at a depth of approximately 300 nm. CL data was measured by Hitachi SU-70 microscope with CL option from Horiba Jobin Yvon.

To compare our findings with the results reported in the literature, DLTS scans with different emission rates in the range of 20–2000 Hz have been measured. The activation energy was obtained as a slope of linear fitting to data points plotted in the Arrhenius diagram (not shown here).

The obtained values of 0.245 eV and 0.56 eV agree well with activation energies of commonly observed E1 and E3 centers in n-GaN [11–13]. Thus trap 1 and trap 2 have been assigned to E1 and E3, respectively.

As to the origin of those signals, there is still no consensus in the GaN community, however, some new interpretations seem to be plausible.

In 2002, Fang [11] suggested that the E1 center could be attributed to the divacancy V_{N}–V_{Ga}. The low formation energy of that complex obtained by DFT (density functional theory) confirms that finding [14]. However, the studies of the E1 trap in GaN grown on AlN and sapphire analyzed by Ito [15] showed that threading dislocation density (TDD) has no impact on the E1 trap. On the other hand, some results predict that the E1 center is related to a point [13] or extended defect [12, 16]. Soh et al. [17] suggested that an extrinsic point defect, such as oxygen, could be responsible for this trap. Finally, in our recent paper [18], we proposed a model where the E1 center is a two-defect level assigned to VN-related defect and C_{Ga}–V_{N} (+/0), respectively.

As one can see, there is no clear hypothesis on the origin of the E1 trap. In the case of the E3 trap, the situation is very similar. This level does not change its concentration after electron irradiation, thus, simple point defects such as V_{N}, V_{Ga}, G_{i}, or N_{i} can be excluded from considerations [19]. There were some indications that N_{Ga} anti-site could be responsible for that defect [20], however, first-principles calculations shown by Lyons [21] revealed high formation energy of N_{Ga}. Furthermore, the deep level related to N_{Ga} is expected to be located much deeper in the bandgap ($E_c = -1.06$ eV) [21].

In 2020, Horita and co-authors [22] published results of DLTS analysis carried out for E3 trap concentration measured by the isothermal DLTS technique at 300 K. The authors have found similar results to the E3 trap behavior presented in this manuscript. The authors have concluded that depending on the growth conditions, E3 trap concentration can vary up to 2 orders of magnitude across the diode structure. It was found that lower GaN growth rate results in higher E3 trap concentration. Moreover, Horita assigned the E3 trap level to Fe or Fe-related defect since E3 trap concentration has an almost one-to-one relation with Fe concentration measured by SIMS (secondary ion mass spectroscopy) technique. As to the source of iron, the authors proposed that some reactor components acted as a Fe source that could be introduced into GaN layers at high temperatures.

Finally, Horita [22] reported only E3 trap variation across the wafer but surprisingly did not observe a similar effect for the E1 level. In our opinion, this can be due to different growth conditions used for SBDs structures grown in both studies. Unfortunately, authors do not give GaN growth details such as III/V ratio, growth temperature, or pressure, and thus the structures can not be compared directly.

Based on the above considerations, one could expect similar relation between E1 and Fe concentration. Unfortunately, we do not have SIMS data for that sample, but such experiments are planned to be done in the near future.

We believe that SIMS results would confirm or negate Fe origin for the E1 trap level.

4. Conclusions

In this paper, we have presented the results of a DLTS-based analysis of two traps commonly observed in n-GaN, the E1 and E3, respectively. We have found that the concentration of both traps strongly depends on the distance to the original wafer edge and decreases over two orders of magnitude as the distance increases. Moreover, we speculate that both deep levels can be related to iron or its complexes.

Acknowledgments

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