Deep levels in n-type Schottky and p^+-n homojunction GaN diodes

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ABSTRACT

The deep level spectra in both p^+-n homojunction and n-type Schottky GaN diodes are studied by deep level transient spectroscopy (DLTS) in order to compare the role of the junction configuration on the defects found within the n-GaN layer. Both majority and minority carrier DLTS measurements are performed on the diodes allowing the observation of both electron and hole traps in n-GaN. An electron level at E_c-E_t=0.58 and 0.62 V is observed in the p^+-n and Schottky diodes, respectively, with a concentration of ~3-4×10^{14} cm^{-3} and a capture cross section of ~1-5×10^{-15} cm^2. The similar Arrhenius behavior indicates that both emissions are related to the same defect. The shift in activation energy is correlated to the electric field enhanced-emission in the p^+-n diode, where the junction barrier is much larger. The p^+-n diode configuration allows the observation of a hole trap at E_t-E_v=0.87 eV in the n-GaN which is very likely related to the yellow luminescence band.

INTRODUCTION

GaN is a material of great interest due to its wide applicability in optoelectronics and high temperature electronics. However, the role of electrically active defects and their sources in GaN are still not well understood [1-5]. Thus, further studies regarding the deep levels found within the n-GaN bandgap which are associated with such defects are needed. While p^+-n diode configurations are used for GaN LED's and lasers applications, n-Schottky diodes are of interest for GaN FET's. Thus, the role of the device configuration on the deep level spectrum is also of great interest. In this article deep level transient spectroscopy (DLTS) is used to study the deep level spectra in p^+-n and n-Schottky GaN diodes and the fundamental properties of specific deep levels are explored. Both majority and minority carrier injection conditions are used for the DLTS measurements which allows the observation of both electron and hole traps in the n-GaN layer found up to ~0.9 eV from the conduction and valence bands, respectively.

EXPERIMENT

GaN test devices were grown by MOCVD using a horizontal flow reactor on a c-sapphire substrate. A 0.5 μm-thick unintentionally doped n-type layer (n=3x10^{16} cm^{-3})

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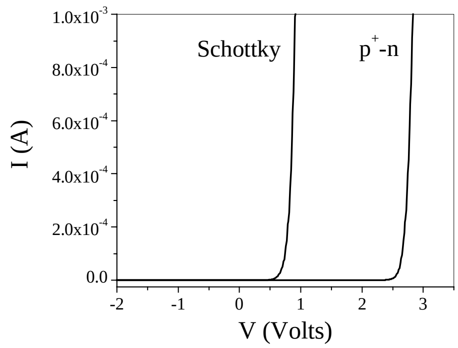

Figure 1: I-V curves measured at 300K for the n-Schottky and p^+-n GaN diodes. As expected, a much larger built-in voltage is observed for the p^+-n diode.

was first deposited followed by 0.5 µm-thick Si-doped (n=3x10^{18} cm^{-3}) and 1 µm-thick Si-doped (n=8x10^{18} cm^{-3}) GaN layers [6]. A 1.2 µm-thick unintentionally doped n-GaN layer (n=3.5x10^{16} cm^{-3}) was next deposited for the n-Schottky and p^+-n diodes, followed by a 0.16 µm-thick Mg-doped GaN layer (p=0.8-1x10^{18} cm^{-3}) for the p^+-n structure. Pd/Au and Ni were next deposited providing ohmic and Schottky contacts to the GaN. Under these conditions the depletion region is fully contained in the n-GaN layer in both types of diodes. Back contact to the 1 µm-thick n-GaN layer was provided by a Ti/Al/Ni/Au metal layer. The diode size was ~0.23 mm^2, with a reverse leakage current at –1 V of ~4x10^{-10} and ~2x10^{-9} A/cm^2 and a turn-on voltage of ~2.2 and ~0.4 V for the p^+-n and Schottky diodes, respectively, at 300 K (Fig. 1).

DLTS experiments were performed using a Boonton capacitance meter at 1 MHz. Rate windows between 4 and 200 sec^{-1} were used with a –1 V quiescent voltage applied to the diodes for all measurements. Majority carrier trap filling was ensured by a 10 ms-long pulse under a fill pulse voltage (V_p) of –0.2 V for both the p^+-n and Schottky diodes. Depth resolved DLTS measurements of the majority carrier traps were achieved by changing V_p from –0.2 to 1, 1.5, and 2 V in the p^+-n diode. Positive V_p also provided minority carrier injection in the p^+-n sample, allowing the observation of hole traps in the n-side of the junction [7].

RESULTS AND DISCUSSION

In this section the majority carrier traps (electron traps) for the n-Schottky diode are first discussed and followed by a comparison to those found in the p^+-n diode. This comparison is followed by a study of the minority carrier traps (hole traps) found in the n-side of the p^+-n diode.

The majority carrier DLTS spectrum for the n-Schottky diode is shown in Fig. 2. A prominent peak is observed which corresponds to an electron trap found within the n-GaN layer with an activation energy of E_c-E_t=0.62 eV, as extracted from the Arrhenius

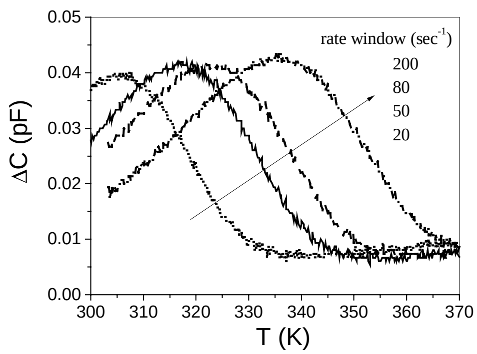

Figure 2: DLTS spectra for the n-Schottky GaN diode under V_p=-0.2 V for different rate windows.

plot (Fig. 3), and with a concentration of ~4.1×10^{14} cm^{-3}. The capture cross section for the 0.62 eV level is ~5×10^{-15} cm^2.

As seen in Fig. 2, the DLTS peak height of the E_c-0.62 eV trap showed no dependence on rate window. Moreover, theoretical modeling of an ideal single state at E_c-0.62 eV yielded a FWHM/T_{peak} ratio of 0.11, in close agreement with the measured value of 0.14. Together, these observations suggest a point defect as the source for this electron trap [7].

In contrast to the Schottky results, a conventional DLTS filling pulse of V_p=-0.2 V does not reveal the presence of the E_c-0.62 eV level in the p^+-n diode (Fig. 4). However, as V_p is increased so that the depletion region width reduces, approaching the heavily Mg-doped cap layer, the trap reappears. Note that at 2 V (still below the turn-on voltage) and 400 K the current injected into the p^+-n diode is still ≤1 nA indicating that

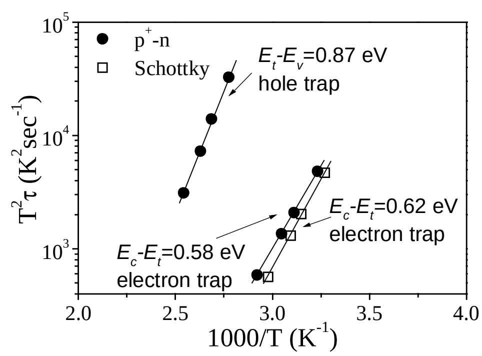

Figure 3: Arrhenius behavior of the electron and hole traps found in both p^+-n and n-Schottky GaN diodes.

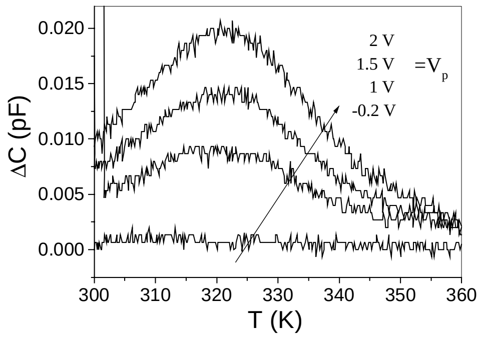

Figure 4: DLTS spectrum obtained from the p+-n GaN diode for a rate window of 50 sec^{-1} as a function of fill pulse bias voltages.

such a change in the DLTS peak height is most likely due to an increase in the trap concentration close to the Mg-doped cap but still within the n-GaN layer. The activation energy for this electron trap was found to be E_c-E_t=0.58 eV (Fig. 3) and the capture cross section ~1×10^{-15} cm^2. At V_p=2 V the concentration of this level is ~2.7×10^{14} cm^{-3}, very similar to that observed in the n-Schottky diode. Indeed, as shown in Fig. 3 the Arrhenius behaviors of the 0.58 and 0.62 eV levels are very similar which clearly indicates that they are very likely the same level.

However, note that for a given rate window (e.g. 50 sec^{-1} in Figs. 2 and 4) the DLTS peak associated with the 0.58-0.62 eV level shows a small shift to higher temperatures from the Schottky to the p$^+$-n diode, which in turn produces the 0.04 eV shift in activation energy shown in Fig. 3. Such a shift can be explained in terms of the difference in the magnitude of the electric field present in the depletion region in both samples. Indeed, Fig. 1 shows a turn-on voltage of ~0.4 V and ~2.2 V for the Schottky and p$^+$-n diodes, respectively, which implies that a larger junction barrier is present in the p$^+$-n diode. This indicates that the electric field is much larger in the p$^+$-n sample. Under these conditions emission from the 0.58-0.62 eV level is enhanced by the larger field in the p$^+$-n diode, producing a decrease in the measured activation energy [7].

The E_c-E_t=0.58-0.62 eV level shows a similar Arrhenius behavior as the E2 level previously reported in n-Schottky diodes [2], and is likely produced by the same defect. The E2 level concentration has been observed to depend on the Cp_2Mg flow rate during growth of the n-GaN layer, increasing under larger flow conditions [4]. As shown in Fig. 4, the 0.58 eV level emission is highly dependent on fill pulse bias, increasing in magnitude by at least a factor of 15 from –0.2 to 2V, which corresponds to a shift in the depletion region width of ~0.2 μm towards the p$^+$-side of the junction. Such a large increase in concentration tracks the residual Mg concentration profile in the n-side of the junction observed by second ion mass spectroscopy [5].

Finally, the DLTS spectrum at V_p=2 V for the p$^+$-n diode is shown in Fig. 5. A large negative peak is observed in the DLTS spectrum that was not be observed for

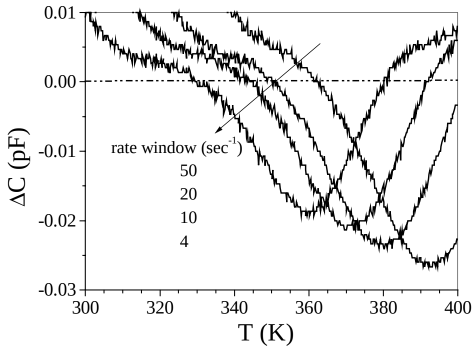

Figure 5: Minority carrier DLTS spectra from the p^+-n GaN diode at V_p=2 V for different rate windows.

negative fill pulse voltages. This peak was also observed for V_p=1 and 1.5 V with a magnitude decreasing with decreasing V_p. The injected current under these conditions is below 1 nA and the depletion region width is 30 times larger on the n-side than on the p-side of the p^+-n junction. Moreover, this hole trap could not be observed in the n-Schottky diode (with V_p=0.4 V) as would be expected from such a junction, where minority injection is not possible. Together, these observations indicate that this DLTS feature is indeed a minority carrier hole trap found in n-GaN. This hole trap shows an activation energy of E_t-E_v=0.87 eV (Fig. 3) with a concentration $\geq 3.7\times10^{14}$ cm^{-3}, and a capture cross section of ~6×10^{-14} cm^2. The position in the bandgap of the 0.87 eV hole trap correlates very well with a deep level at E_c-E_t=2.64 eV measured under optical excitation by deep level optical spectroscopy (DLOS) [5] and observed in both p^+-n and n-Schottky GaN diodes. It is also close to a deep level previously reported in n-Schottky diodes and associated with the yellow luminescence in n-GaN [1], and correlates well with calculated energy levels associated with V_{Ga}-O and V_{Ga}-donor complexes [3].

CONCLUSIONS

In summary, DLTS has been used to study and compare deep levels and their electrical signature in n-Schottky and p^+-n GaN diodes. Majority and minority carrier injection during the measurements allowed the observation of both electron and hole traps in the n-GaN layer. The n-Schottky diode shows an electron trap at E_c-E_t=0.62 eV with a concentration of ~4.1×10^{14} cm^{-3} and a capture cross section of ~5×10^{-15} cm^2. A deep level at E_c-E_t=0.58 eV is also observed in the p^+-n diode with a concentration of ~2.7×10^{14} cm^{-3} and a capture cross section of ~1×10^{-15} cm^2. The similar Arrhenius behavior of the two electron traps in both types of diodes indicates that the two levels are likely related to the same defect. The shift in the activation energy from 0.62 to 0.58 eV between the n-Schottky and p^+-n diodes is due to an electrical field enhancement of the emission rate in the p^+-n diode. Under minority carrier injection a hole trap at E_t-E_v=0.87

eV with a concentration ≥ 3.7×10^{14} cm^{-3} and a capture cross section of ~6×10^{-14} cm^{2} is observed in the n-GaN layer. This level was only observed in the p^+-n diode due to the fact that hole injection is needed for this measurement and is not possible for an ideal Schottky junction. The E_t-E_v=0.87 eV is likely related to the yellow band [1], and correlates very well with a level observed both in n-Schottky and p^+-n GaN diodes by DLOS [5].

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