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Deep Levels in GaN *p–n* Junctions Studied by Deep Level Transient Spectroscopy and Laplace Transform Deep-Level Spectroscopy

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p^+–n GaN diodes were studied by means of conventional deep level transient spectroscopy and Laplace transform deep-level spectroscopy methods within the temperature range of 77–350 K. Deep level transient signal spectra revealed the presence of a majority and minority trap of indistinguishable signatures. The Laplace transform deep-level spectroscopy technique due to its superior resolution allows us to unambiguously identify and characterize the traps. The apparent activation energy and capture cross-section for the majority trap were found to be equal to 0.63 eV and 2×10^{-16} cm^2 and for the minority trap 0.66 eV and 1.6×10^{-15} cm^2. It has been confirmed that the Laplace transform deep-level spectroscopy technique is a powerful tool in characterization of the traps of close signatures.

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1. Introduction

Defects in semiconducting *p–n* junctions operating as light emitters play a crucial role as deteriorating device performance recombination centers. Gallium nitride (GaN) and related III-nitride compounds are widely used in light emitting diodes and laser diodes. There is a vast data on deep-levels signatures for GaN based materials. In particular there is a family of commonly observed electron and hole traps of similar signatures around 0.6 eV. Their signatures are so closed that exact identification is difficult. Deep-level transient spectroscopy (DLTS) is the technique used to study properties of defects in semiconductors. It is well known that the resolution and sensitivity of the Laplace transform deep-level spectroscopy (LDLTS) is much better as compared to the conventional DLTS method. In particular with this technique the deep-levels of similar properties can be probed and identified [1].

In present paper we report on the results of the measurements performed on GaN p^+–n junctions with the use of conventional DLTS and LDLTS methods. The conventional DLTS measurements reveal the presence of a single dominant electron trap whereas LDLTS studies yield two distinct electron and hole traps.

2. Experiment

GaN layers, Si-doped to nominal concentration of about $N_{\mathrm{Si}} = 5 \times 10^{18}$ cm^{-3} were grown by metal-organic vapor-phase epitaxy (MOVPE) technique on Ga-polarity (0001) surface of GaN substrates. The thickness of Si-doped layer was set to 0.51 μm. Subsequently Mg-doped GaN layer of the thickness of 0.53 μm was grown. This latter layer had the nominal Mg concentration $N_{\mathrm{Mg}} = 5 \times 10^{19}$ cm^{-3}. Two different ohmic contacts were processed to the whole structure: Ni(25 nm)/Au(20 nm) contact supplied to the *p*-type material and Ti(30 nm)/Al(70 nm) contact completed to the *n*-type material.

Details on the basic properties of the studied diodes obtained with the use of standard characterization techniques (current–voltage and capacitance–voltage measurements) are given in [2].

DLTS measurements were performed within the temperature range from 77 K to 350 K on two different systems: the lock-in based DLS-82E system manufactured by Semitrap Company (System 1) and LDLTS system developed at the Institute of Physics, Polish Academy of Sciences in Warsaw and at the Microelectronics and Nanostructure Group, School of Electrical and Electronic Engineering at the University of Manchester (System 2). The latter can operate in two modes: conventional (lock-in and boxcar) and the Laplace transform DLTS.

3. Results and discussion

In Fig. 1 DLTS signal obtained with the help of both systems are shown for comparison. The measurements were performed at the reverse bias equal to −2 V, the

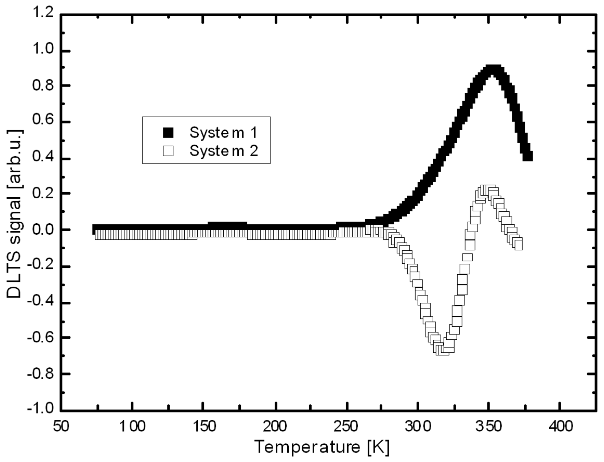

Fig. 1. Typical conventional lock-in DLTS temperature scans with the use of the System 1 and System 2.

rate window equal to 10 Hz and 0.3 V filling pulse height. The width of the pulse was equal to 100 μs.

The dominant DLTS signal observed around 300 K obtained with the help of conventional DLTS system is a broad, featureless maximum of majority-like behavior. The signal obtained with the System 2, operating also in conventional lock-in mode is on the contrary composed of two distinct minority- and majority-like contributions. Both majority and minority signals are close, overlap so that it is impossible to determine their signatures. Thus the results obtained with both systems are confusing and unambiguous.

LDLTS system with its improved resolution overcomes this obstacle. In Fig. 2 typical Laplace spectra for the majority (Fig. 2a) and minority signals (Fig. 2b) are shown. Both spectra were measured at reverse bias equal to -2 V, filling pulse 0.3 V and filling pulse width 100 μs. It is evident that the trap level responsible for the minority signal exhibits perfect exponential behavior whereas that connected with majority trap is associated with the trap of certain energy distribution. In the studied p^+–n junctions depletion region extends mainly on the n-side of the junction for its lower doping level. Therefore the majority DLTS signal can be assigned to electron trap whereas minority signal is associated with a hole trap.

The Arrhenius plots obtained from the spectra measured at various temperatures for both signals are shown in Fig. 3. In order to compare the results with those found elsewhere the Arrhenius plots obtained by others are also collected in Fig. 3. The Arrhenius plots associated with electron trap are labeled as E and the ones associated with hole traps — as H. In the figure only selected data reported by others are given, for some authors do not present the Arrhenius plots. However it is evident that the signatures for hole and electron traps are close.

Apparent activation energy and capture cross-section determined with the help of the both systems are given

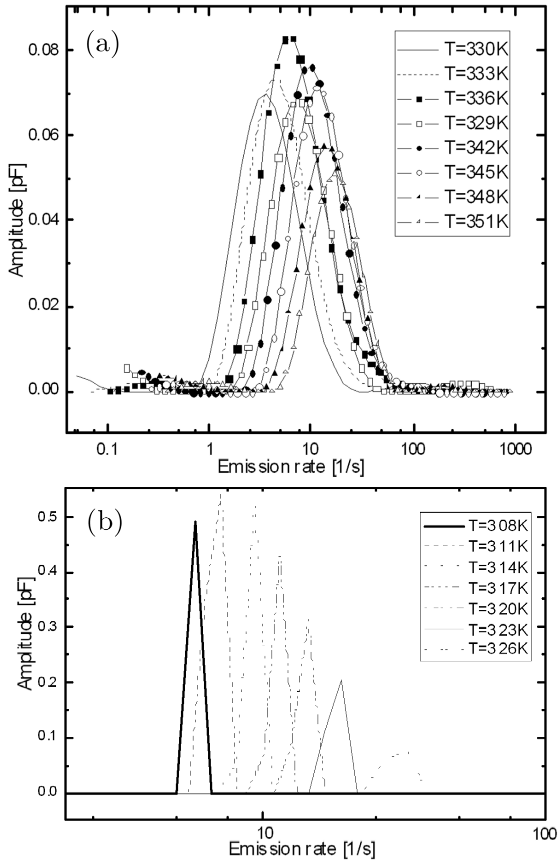

Fig. 2. (a) Laplace spectrum for majority trap. (b) Laplace spectrum for minority trap.

in Table. As expected, the signatures of the electron trap obtained by the systems are close.

TABLE

Apparent activation energy and capture cross-section for the traps in p^+–n GaN junctions.

Sample	E DLS 82E System 1	E DLTS, LDLTS System 2	H LDLTS System 2	D3 [3]
E_a [eV]	0.63	0.63	0.66	0.59
σ [cm^2]	2×10^{-16}	2.9×10^{-16}	1.6×10^{-15}	1.7×10^{-16}

There are numerous reports on electron trap of properties similar to the properties of the trap E found by us, but there are no reports on the trap of close signature. In Fig. 3 few examples are shown for comparison. These traps are commonly observed in undoped and Si doped GaN. Different authors attribute the trap either to a single defect (vacancy) or to V_{Ga}–O_N complex [7]. The authors agree that the trap has metastable property. We have also found that this trap has thermally activated capture cross-section [2], which confirms its metastable character. For such a trap broad LDLTS signal is anticipated which is actually observed for the E trap (cf. Fig. 2a). As for the hole trap solely the Arrhenius plot

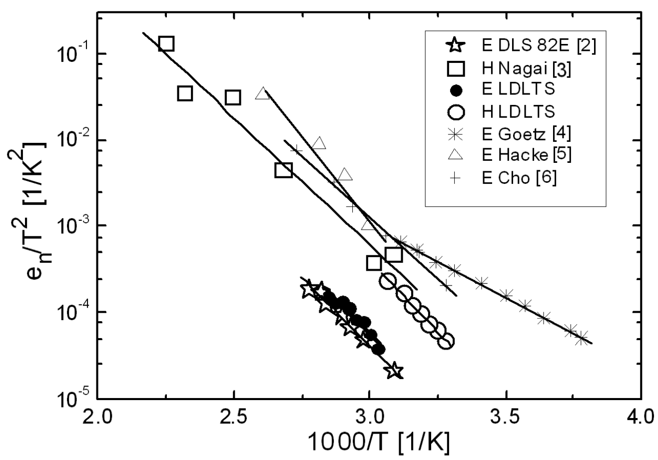

Fig. 3. Arrhenius plots for electron and hole traps in GaN. Solid lines are the best least squares fits. E — electron traps, H — hole traps.

for the trap D3 observed by Nagai et al. [3] is shown in Fig. 3. There are reports on many other hole traps in GaN:Mg, but their location on Arrhenius plots is far away from our data or authors do not present related Arrhenius plots.

In Table signatures for the trap D3 observed by Nagai et al. are also included for comparison. In spite of different activation energy and capture cross-section, the data for this hole trap are located on the Arrhenius plot close to the data obtained by us for the hole trap. The origin of the defect related to the H trap is unknown. Based on the LDLTS spectrum for the trap H it may be concluded unambiguously that it has to be a point defect.

4. Conclusions

In this study we present the results of investigation on p^+–n GaN diodes by means of conventional DLTS and LDLTS methods within the temperature range of 77–350 K. DLTS signal spectra reveal the presence of a dominant majority trap with activation energy equal to $E_2 = 0.63$ eV and capture cross-section of 2×10^{-16} cm^2 (as obtained from the Arrhenius plots). Its capture cross-section is thermally activated with the barrier for capture equal to 0.2 eV [2]. No minority trap is detected for the samples under study by DLTS. On the contrary, the LDLTS measurements yield not only the presence of a trap of signature similar to that found by DLTS but additionally a minority trap of activation energy equal to 0.66 eV and capture cross-section equal to 4.5×10^{-15} cm^2. The junction under study has the depletion width extending on both sides of the junction with n-side wider than the p-side since the nominal acceptor concentration (10^{19} cm^{-3}) exceeds the donor concentration (10^{18} cm^{-3}). Consequently, it may be concluded that the DLTS measurements performed on GaN p^+–n junctions detect solely a majority electron trap while the LDLTS monitors additionally a minority hole trap.

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