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Deep traps in GaN-based structures as affecting the performance of GaN devices

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ABSTRACT

New developments in theoretical studies of defects and impurities in III-Nitrides as pertinent to compensation and recombination in these materials are discussed. New results on experimental studies on defect states of Si, O, Mg, C, Fe in GaN, InGaN, and AlGaN are surveyed. Deep electron and hole traps data reported for GaN and AlGaN are critically assessed. The role of deep defects in trapping in AlGaN/GaN, InAlN/GaN structures and transistors and in degradation of transistor parameters during electrical stress tests and after irradiation is discussed. The recent data on deep traps influence on luminescent efficiency and degradation of characteristics of III-Nitride light emitting devices and laser diodes are reviewed.

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1. Introduction

Wide-bandgap III-Nitrides have grown into one of the most important semiconductor materials systems with vast applications in visible-UV light emitting devices (LEDs) and laser diodes (LDs), high-power transistors and rectifiers, high-frequency devices. Deep traps in such devices can play a very important role. This is particularly so for the III-Nitrides because these compounds are commonly grown on lattice mismatched substrates, with a large lattice mismatch between individual epitaxial layers. Growth is performed at high temperatures potentially conducive to strong impurity contamination, high concentration of point defects and high strain caused by the difference in thermal expansion coefficients. All this can result in high density of extended defects and centers with deep levels. Initial deep center defects studies were, therefore, aimed at establishing the properties of major native defects, impurities and dopants and their complexes both theoretically and experimentally. Also, one of the most important tasks was to study the electronic structure of extended defects in III-Nitrides. These studies in III-Nitrides were seriously complicated by the wide-bandgap of most nitrides necessitating the development of new methods of deep traps spectroscopy. Indeed, the bandgap of GaN is 3.4 eV at room temperature, while the depth of deep traps that can be easily scanned by the standard deep levels transient spectroscopy (DLTS) due to Lang [1] is usually ~1 eV from the conduction or valence band. Thus, the probed regions of the bandgap even in GaN miss the most important midgap region, the more so for wider bandgap InAlGaN ternaries and quaternaries. This can in principle be remedied by increasing the high temperature in the DLTS temperature scan, but the leakage current of Schottky diodes or *p*–*n* diodes in GaN-based devices is usually relatively high even at room temperature which makes it very difficult to carry out reliable capacitance measurements at temperatures exceeding ~500 K. Undoped III-Nitrides grow usually preferentially n-type, so minority carriers traps in such films had to be studied on Schottky diodes by the DLTS version with optical injection pulse, the so called optical DLTS (ODLTS) [2]. The as-grown, annealed or irradiated III-Nitrides are often semi-insulating and deep traps in them have to be detected by using the photoinduced current transient spectroscopy (PICTS or OTCS) which is similar to DLTS, but utilizes photocurrent relaxations induced by optical injection pulse [3–6].

The III-Nitrides films and layers are often heavily compensated so that standard DLTS measurements on them are not reliable [1]. In that case current version of DLTS (CDLTS) (see [7] and references therein) is often an answer. It also helps in analysing the spectra of deep traps in p-type nitrides because the depth of p-type dopants in nitrides is relatively high and causes strong freeze-out of material at temperatures below room temperature.

Admittance spectroscopy (see e.g. [8]) and capacitance–voltage (*C*–*V*) profiling in the dark or under illumination (LCV) [7,9] were found to be very useful in determining the thermal and optical ionization energy of deep traps near the Fermi level in compensated nitrides. These techniques also proved very useful in analyzing the electrical properties and charge distribution in quantum well or multi-quantum-well structures.

In order to circumvent the problem with high ionization energy of traps in GaN and AlGaN the deep levels optical spectroscopy (DLOS) [10] was widely adopted in nitrides studies. In this method the bandgap is scanned not by sweeping the temperature, as in DLTS, but rather by sweeping the photon energy of excitation light.

Because the dislocation density in III-Nitrides is usually quite high methods had to be developed to detect deep traps decorating dislocations as well as the states that belong to dislocations proper. Here a wide application was found for the method employing DLTS peaks amplitude measurements as a function of the injection pulse length (due to Wosinski [11]).

Additional problems in all measurements involving light excitation are caused by the necessity to employ very short-wavelength light sources in DLOS, ODLTS, PICTS, photoluminescense (PL) spectroscopy. The results of the initial round of these theoretical and experimental studies have been summarized in several reviews [12–18]. Theory pointed to the dominant role of gallium vacancy (V_{Ga}) acceptors in n-type nitrides and nitrogen vacancy donors (V_N) in p-type nitrides. Experimental studies were able to map out the major electron and hole traps in *n*-GaN and partly in *p*-GaN. Identification of the possible origin of the traps, when it was done, understandably relied very heavily on the results of radiation studies which was reflected in the general tenor of the review articles. As a pleasant surprise it was found that the densities of deep traps in nitrides are not as high as could be anticipated and the dislocations are far less detrimental to the devices performance than for other III-V materials. The contribution of Shockley–Read–Hall (SRC) recombination in nitride light emitters was not found to be the major factor. At the same time, radiation experiments showed that the radiation tolerance of III-N devices is one-two orders of magnitude higher than for Si or GaAs-based devices and does not pose an immediate problem in device applications. Hence, the somewhat decreased interest to defects with deep centers in nitrides in recent years.

However, lately the new understanding of the role of deep traps in III-Nitride devices starts to emerge. It is based both on the results of new theoretical calculations and on thorough investigations of the role of deep traps in performance of LEDs, LDs, HEMTs and in their degradation under electrical stress. For example, theoretical work has re-assessed the role of C in III-Nitrides showing it to be a deep trap impurity with the midgap acceptor level and a deep donor level. For the main shallow acceptor, Mg, theory shows that it, in fact, has all the characteristics of deep level defects. These findings have potentially profound consequences for interpretation of compensation mechanisms in III-Nitrides (very important for optimizing growth of semi-insulating buffers in HEMTs). They are also important for attribution of defect related PL bands in III-Nitrides which is of great interest in understanding the behavior of UV-LEDs and their degradation.

Recent experiments point to a serious role of deep trap defects in determining the quantum efficiency and the threshold current of LEDs and LDs, trapping in HEMTs and the way these devices deteriorate when operated under high driving current conditions typical of their practical use. It seems that traps decorating dislocations play a particularly prominent part in these effects. A new understanding is also accumulating on possible links between the changes induced by irradiation and the degradation of devices during electrical stress testing. It seems that these efforts have to be systematized in order to coordinate further studies in that direction. This is the major aim of the present review.

The structure of the paper is as follows. In Section 2, we briefly describe the previously obtained results of theoretical calculations