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Detailed characterization of deep level defects in InGaN Schottky diodes by optical and thermal deep level spectroscopies

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Schottky diode properties of semitransparent Ag(4 nm)/Au(4 nm) metal stack on $In_{0.2}Ga_{0.8}N$ were investigated and defect characterization was performed using capacitance deep level transient (DLTS) and optical spectroscopy (DLOS). DLTS measurements made on the $In_{0.2}Ga_{0.8}N$ Schottky diodes, which displayed a barrier height of 0.66 eV, revealed the presence of two deep levels located at Ec-0.39 eV and Ec-0.89 eV with nearly identical concentrations of $\sim 1.2 \times 10^{15}$ cm^{-3}. Three deeper defect levels were observed by DLOS at Ec-1.45 eV, Ec-1.76 eV, and Ec-2.50 eV with concentrations of $1.3 \times 10^{15} cm^{-3}$, $3.2 \times 10^{15} cm^{-3}$, and 6.1×10^{16} cm^{-3}, respectively. The latter, with its high trap concentration and energy position lying 0.4 eV above the valance band, suggests a possible role in compensation of carrier concentration, whereas the mid-gap positions of the other two levels imply that they will be important recombination-generation centers [doi:10.1063/1.3631678]

There has been great interest in GaN and related alloys due to their superior properties such as high breakdown field, good thermal conductivity, and high electron saturation velocity.[1] While $Al_xGa_{1-x}N$ alloys are important for power devices and deep ultraviolet emitters, $In_xGa_{1-x}N$ alloys with bandgaps ranging from 0.7 to 3.4 eV covering the entire visible spectrum are of interest for many future optoelectronic and energy applications. In addition, high In composition $In_xGa_{1-x}N$ alloys also possess significant potential for high speed device applications due to their small effective mass and high mobility.[2] For all such device applications, device characteristics and performance are greatly impacted, and degraded, by the presence of variety of growth related defects. Recently, it has been shown that the defect states formed either during the growth process or as a result of device operation tend to act as non-radiative recombination centers and/or create leakage pathways that degrade vertical conduction in $In_xGa_{1-x}N$-based quantum well light emitting diodes (LEDs) and blu-ray laser diodes.[3,4] However, the current state of knowledge about the electronic properties of defects in $In_xGa_{1-x}N$ is very limited and has not been well explored. A contributing reason is the difficulty in obtaining high-quality InGaN Schottky diodes (SDs) that would enable quantitative investigation of electronic defect properties by capacitance-based transient techniques, in particular deep level transient (DLTS) and optical spectroscopy (DLOS). To date, there have been sparse reports related to the SD properties of $In_xGa_{1-x}N$. These studies have generally revealed poor quality diodes, even for low In composition alloys compared to SDs those on GaN,[5,6] which have been attributed to high background doping and difficulties in obtaining high quality $In_xGa_{1-x}N$ layers,[7,8] larger amount of surface defects compared to GaN,[9] and the presence of surface accumulation layers.[7] This study focuses on the development of high quality $In_{0.2}Ga_{0.8}N$ SDs and subsequent electrical and trap characterization using both DLTS and DLOS measurements.

Plasma-assisted molecular beam epitaxy (PAMBE) was used to grow 300 nm thick, unintentionally doped (uid) $In_xGa_{1-x}N$ layers on an n-type GaN template (Kyma, carrier density $\sim 1 \times 10^{18}$ cm^{-3} and dislocation density $\sim 10^8$ cm^{-2}). PAMBE growth optimization was guided using a growth model developed for Ga-polar InGaN reported elsewhere.[10] The $In_{0.2}Ga_{0.8}N$ composition was confirmed by high resolution triple-axis x-ray diffraction measurements. After growth, the sample was cleaned by dipping into the HCl in order to get rid of the In droplets and then standard organic cleaning process followed by acetone/methanol/isopropanol. Optical (contact) lithography was used to define patterns after which O_2 ashing and HCl:DI (1:10) were used to remove photoresist residual and native oxides, respectively. An electron beam evaporated Ag(4 nm)/Au(4 nm) metal stack was used as a semitransparent Schottky contact to allow penetration of monochromatic light used in DLOS measurements. Devices were isolated using Cl_2–based reactive ion etching. Finally, a Ti:Al:Ni:Au metal stack was evaporated for ohmic contacts on the n^+-GaN template.

Fig. 1 shows the electrical properties of the Au/Ag/$In_{0.2}Ga_{0.8}N$ SD by current voltage (*I-V*) and capacitance-voltage (*C-V*) measurements measured at 300 K. Almost three orders of magnitude rectification factor is evident from Fig. 1(a). Also, the reverse current density of the Au/Ag/$In_{0.2}Ga_{0.8}N$ SC shows field dependence, i.e., no saturation, which might be either due to the voltage dependency of the barrier height (perhaps due to image force lowering), and/or tunneling, or is due to generation of current via bandgap states in the depletion region.[11] From the *I-V* analysis, ideality factor, barrier height, and saturation current density parameters were determined to be $n = 1.34$, $\Phi_b = 0.66$ eV,

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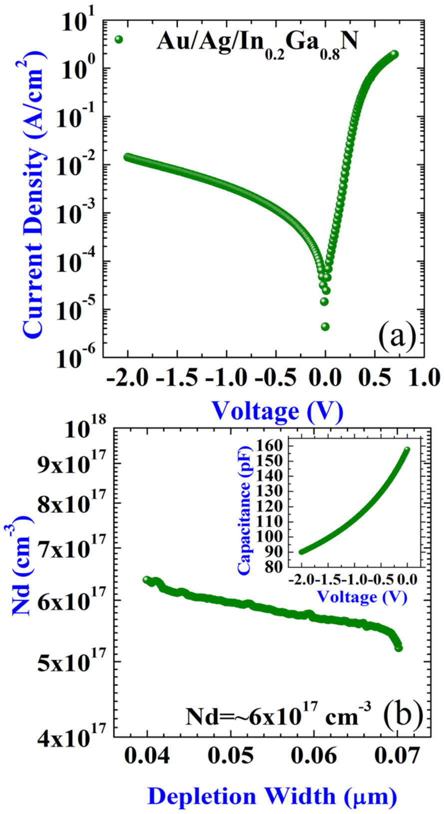

FIG. 1. (Color online) (a) *I-V* and (b) *C-V* characteristics of the Au/Ag/$In_{0.2}Ga_{0.8}N$ Schottky diode.

and $\sim 2 \times 10^{-5}$ A/cm^2, respectively, by modeling the measured data as a standard Schottky barrier following simple thermionic emission.[11] The relatively good ideality factor (i.e., close to 1) compared with prior reports of InGaN SDs supports that thermionic emission is the dominant current transport mechanism.[5,6] The characteristic energy of the Schottky barrier, qE_{00}, was calculated to be 10.2 meV, which is lower than the room temperature kT value of 25.86 meV, further supporting the presence of a strong, nearly ideal thermionic emission process.[11]

The inset of Fig. 1(b) shows *C-V* measurements between -2 V and 0 V. Fig. 1(b) shows the calculated values of the doping density as a function of depletion depth and although this is a uid layer, a reasonably uniform n-type background doping concentration of $\sim 6 \times 10^{17}$ cm^{-3} is observed, which is relatively high compared to the background level of $\sim 10^{16}$ cm^{-3} typically observed in undoped GaN grown in the same growth system. Such observations are consistent with the incorporation of oxygen impurities during PAMBE growth of InGaN as described by Poblenz *et al.*[12]

With good quality SDs established, DLTS measurements were conducted using the standard double boxcar method with a Boonton capacitance meter operating at 1 MHz on these same devices. capacitance-frequency (*C-f*) measurements confirmed the suitability of the 1 MHz frequency for the transient capacitance measurements with negligible dependence of capacitance on frequency. DLTS measurements were performed using a quiescent reverse bias of $V_r = -0.5$ V, a filling pulse of $V_f = 0$ V for a duration of $t_f = 10$ ms. Two well-resolved electron traps were observed via DLTS, which peaked at 227 K and 384 K for the 10 s^{-1} rate window as shown in Fig. 2. The energy levels and capture cross section values of these traps were determined by Arrhenius analysis to be Ec-0.39 eV, 1.24×10^{-16} cm^2 and Ec-0.89 eV, 1.1×10^{-13} cm^2, respectively, with concentrations of $\sim 1.9 \times 10^{15}$ cm^{-3} and 2.8×10^{15} cm^{-3}. Although in the figure the peak heights appear quite similar, the difference in actual concentrations comes from the lambda effect correction to the concentration values. Since depletion depth at V = 0 V, $\sim$40 nm as shown in Fig. 1(b), is large in comparison to the distance where the traps are never filled (for the deeper level, the value is only $\sim$2 nm), this distance is neglected. The details of the correction method can be found in Ref. 13. While reports of DLTS-determined traps in InGaN are sparse, Soh *et al.* reported a deep level that appears to be close to the Ec – 0.39 eV trap observed here with similar capture cross section and energy values (1.2×10^{-16} cm^2, 0.40 eV, respectively);[14] however this trap, which in that work was ascribed to In segregation, was observed for 14% InGaN material, and thus its correlation with the state observed here is only speculative.

In order to probe the defect states located in the remainder of the 2.9 eV bandgap, DLOS measurements were performed using a monochromatized quartz-tungsten halogen (QTH) and Xe lamp with photon energies scanned between 0.5-2.0 eV and 1.2-3.6 eV, respectively. Complete DLOS details have been provided elsewhere.[15–18] Both QTH and Xe lamp DLOS measurements were performed at reverse bias of –0.5 V and filling bias of 0 V with filling pulse time of 10 s. The measurement time used was 200 s, which commenced after an 80 s thermal settling time to avoid signals from thermal emission from deep levels. The steady state photo-capacitance (SSPC) for each detected state provides individual trap concentrations and a full photo-capacitance transient analysis enables extraction of the optical cross section from each detected level, from which precise energy level values are obtained.[15–18] Here, the Lucovsky model was applied to fit the measured cross section data, which ignores detailed lattice relaxation effects, for the purpose of this work.[19]

Fig. 3 shows the complete SSPC and transient DLOS spectra for the InGaN Schottky diodes obtained from the monochromatized QTH and Xe lamp sources. The presence of several additional traps that are not detectable by the conventional DLTS method, due to limitations on thermal

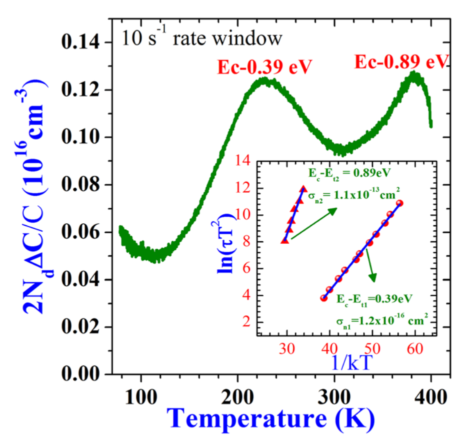

FIG. 2. (Color online) DLTS spectrum of the Au/Ag/$In_{0.2}Ga_{0.8}N$ Schottky diode for the 10 s^{-1} rate window. Inset shows Arhenius plot for the two defect levels observed in the measurement.

emission from very deep states, is immediately obvious. Three additional bandgap states with energy levels at Ec-1.45 eV, 1.76 eV, and 2.50 eV as determined by optical cross section fitting (Figure 3 inset) are revealed. The relatively close match with the SSPC onset energies in the same figure imply that, whatever the physical sources, these defects do not create significant local lattice distortion that would otherwise have been manifested by large Frank-Condon energies that would have created large differences between the energy values obtained by the SSPC onsets and the true optical cross section fitting.[18]

Perhaps, most revealing from the DLOS data is the concentration for these very deep states in the n-type background InGaN layer. Trap concentrations are found to be 1.3×10^{15} cm^{-3}, 3.2×10^{15} cm^{-3}, and 6.1×10^{16} cm^{-3}, for the states at Ec-1.45 eV, 1.76 eV, and 2.50 eV, respectively. Combined with the DLTS-determined traps, the total trap density is at least $\sim 7 \times 10^{16}$ cm^{-3} (note that for states in the lower half of the n-InGaN bandgap, SSPC provides a minimum concentration since we are not accounting for the impact of hole emission processes here).[18] Taking all the observed traps together, the dominant state is clearly the level at Ec-2.50 eV with a trap concentration that is $\sim 20 \times$ of any other detected trap. With this high concentration and its position in the bandgap at $\sim$0.4 eV above the valence band maximum energy, one may expect this trap to be an important compensation center that acts to reduce the n-type background. Based on this premise, and if we choose to ignore the occupancy effects of the other four traps, which is reasonable based on their relatively low concentrations, the concentration of unintentionally incorporated shallow donors that must be present to result in the measured net background n-type doping can be found in a straightforward calculation. With the measured net n-type background concentration of $\sim 6 \times 10^{17}$ cm^{-3}, the Fermi energy position is Ec-0.034 eV. Assuming that the Ec-2.50 eV trap is then fully negatively charged by captured electrons due to its position far below the Fermi level, it contributes 6.1×10^{16} cm^{-3} compensating acceptor-like states and the effective concentration of unintentionally incorporated donor states is therefore $\sim 6.61 \times 10^{17}$ cm^{-3}.

Now considering the other DLOS-detected states, while of lower concentration, the levels at Ec-1.45 eV and 1.76 eV

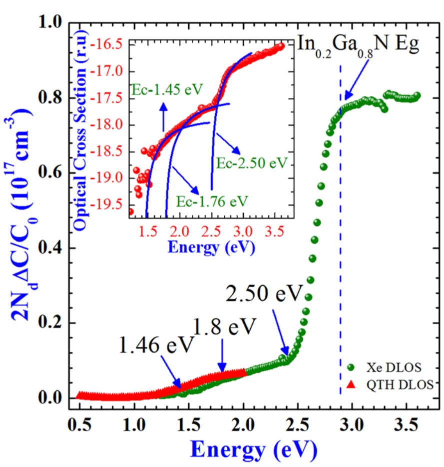

FIG. 3. (Color online) QTH and Xe lamp DLOS measurement on Au/Ag/$In_{0.2}Ga_{0.8}N$ Schottky diode. Inset shows the optical cross section spectrum in relative units (r.u.) obtained from the slope of the transient analysis.

are not negligible and are present in the 10^{15} cm^{-3} concentration range. The positions of both states imply that they may be important recombination-generation centers by facilitating both electron and hole capture due to their mid-gap positions. Indeed, Armstrong *et al.* observed a level found by DLOS at Ev+1.60 eV in $In_{0.17}Ga_{0.83}N$/p-GaN heterojunctions that were grown using similar conditions to quantum-well LEDs.[20]

In summary, we have demonstrated high quality Au/Ag/$In_{0.2}Ga_{0.8}N$ Schottky diodes and have subsequently used them to explore deep levels throughout $In_{0.2}Ga_{0.8}N$ bandgap by using both thermal and optically based trap spectroscopic methods. Five deep states were detected throughout the bandgap of $In_{0.2}Ga_{0.8}N$ with energy levels at Ec-0.39 eV (DLTS), Ec-0.89 eV (DLTS), Ec-1.45 eV (DLOS), Ec-1.76 eV (DLOS), and Ec-2.50 eV (DLOS). While the concentration of the first four levels is on the order of $\sim 10^{15}$ cm^{-3}, the total trap density is dominated by the Ec-2.50 eV level, having a concentration of 6.1×10^{16} cm^{-3}. Overall, the range of energy levels and concentrations for the traps detected here suggest them to play an important role in the observed device behavior and degradation mechanisms of InGaN optoelectronic devices.

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