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Charge Profiling of the p-AlGaN Electron Blocking Layer in AlGaInN Light Emitting Diode Structures

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ABSTRACT

Characterization of operational AlGaInN heterostructure light emitting diodes (LEDs) is critical to their performance optimization and time-to-failure analysis. Typically, device performance data needs to be corroborated with structural information such as layer thicknesses, charge profiles, and the absolute location of the pn-junction. Here, non-destructive testing by capacitance-voltage profiling is being applied to AlGaInN LED structures. Within a large set of samples with different active layer geometry, we observe distinct layers of high mobile charge accumulation. We correlate those with layer thicknesses derived from an x-ray diffraction analysis of the corresponding epiwafers. In this way, we identify the charge maxima as the upper and lower interfaces of the p-type AlGaN electron blocking layer to the neighboring GaN layers. By means of this successful analysis, we now have the opportunity to monitor epi process performance and stability as well as device degradation progress quasi-continuously over the device lifetime in a non-destructive mode.

INTRODUCTION

Group – III nitride light emitting diodes (LEDs) are the prime candidate for energy efficient all solid state lighting in the blue and green spectral region. Active regions comprising GaN/GaInN multi quantum well (MQW) heterostructures act as light emitters, while adjacent GaN and AlGaN layers form a pn-junction to inject electrons and holes, respectively. A critical problem is the controllably and stable injection of either carriers under various operating conditions. A p-type AlGaN electron blocking layer serves to reduce an electron overshoot into the p-layers. Placement, doping, and dimensions thereof are deemed critical to the stabilization of the injection conditions at variable drive current densities. Capacitance-voltage (C-V) measurements have widely been used to investigate such properties in, among others, the AlGaAs/GaAs, InGaAlP/GaAs and ZnO/GaN heterostructure systems.[1-3] Very little, however, is known for LEDs in the AlGaInN system. Recently we succeeded in resolving in individual quantum wells GaN/GaInN active layers.[4] Electric pulse and probe spectroscopy in time domain of forward biased LEDs has been applied by the Sandia group.[5] Here we report an analysis of the p-type AlGaN electron blocking layer in LED-type structures similar to those of blue and green GaN/GaInN MQW LEDs. We correlate C-V data with results of x-ray diffraction (XRD) and find good agreement.

EXPERIMENTAL

LED-type AlGaInN heterostructures have been prepared by metal organic vapor phase epitaxy (MOVPE) in an Emcore D-180 SpectraGaN rotating disc multiwafer system using trimethyl and diethyl adducts of Ga, In, and Al, as well as ammonia. $Ga_{1-x}In_xN$/GaN MQW structures have been embedded in pn-diodes on (0001) sapphire substrate. Ga-face growth was performed along the polar c-axis of GaN. Typical design parameters for the active region are as follows. Several $Ga_{1-x}In_xN$ QWs of nominal well width 3 nm, separated by barriers of nominal thickness of 11 nm have been grown at temperatures above 650 ^oC. There is no intentional doping in the active region. The n-side comprises 4 μ m of GaN:Si doped to a free electron concentration of $\sim 3\times10^{18}$ cm^{-3}. A spacer layer of 20 – 100 nm separates the n-side and the quantum well region. Like the barrier layers, this layer is not intentionally doped resulting in typical electron concentrations of $\sim 3\times10^{16}$ cm^{-3}. The p-side comprises an $Al_yGa_{1-y}N$ electron blocking layer with y = 0.05 – 0.10 and a nominal thickness of 15 – 35 nm. This blocking layer is followed by a GaN p-contact layer of nominal thickness of 350 – 750 nm. Both, electron blocking layer and p-contact layer are Mg doped. The Mg doping concentration typically achieves free hole concentrations of $3-8\times10^{17}$ cm^{-3} in separately grown thick p-GaN layers. Within the set of samples presented here, layer parameters have been varied within the given boundaries.

Epi wafers have been characterized by x-ray diffraction in (0002) geometry. The diffraction pattern has been simulated using a commercial software package for hexagonal crystal lattices. Experimental layer thickness data for the LED-type structures was derived from the simulation. The analysis of x-ray spectra involves the simultaneous fitting of some 25 parameters. While we have good confidence in the resulting data, error bars of +/- 10 % are possible. C-V data may or may not be taken in exactly the same location of the 2-inch wafer. Data on epi wafers have then been processed using a (350 μ m)^2 LED mask set. The active area of the mesa was slightly below that. Electro-optical and capacitance-voltage characterization was then performed on fully processed and wire bonded dies. Capacitance was measured at room temperature in the dark using a 10 mV AC modulation at 1 MHz.

RESULTS AND DISCUSSION

Measured capacitance as a function of bias voltage ranging from forward injection conditions to deep depletion under reverse bias is shown in Fig. 1. The applied bias is swept from +2 V to -20 V. The measured capacitance is in the range of 20 pF to 50 pF. The capacitance shows several distinct steps. It is reasonable to assume that the major contribution to the capacitance stems from the depletion of carriers near the actual pn-junction in the device.

Treating the capacitance in the model of a planar capacitor, the two plates of which are formed by the opposite ends of the depletion zone, the capacitance *C* is given by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (1)$$

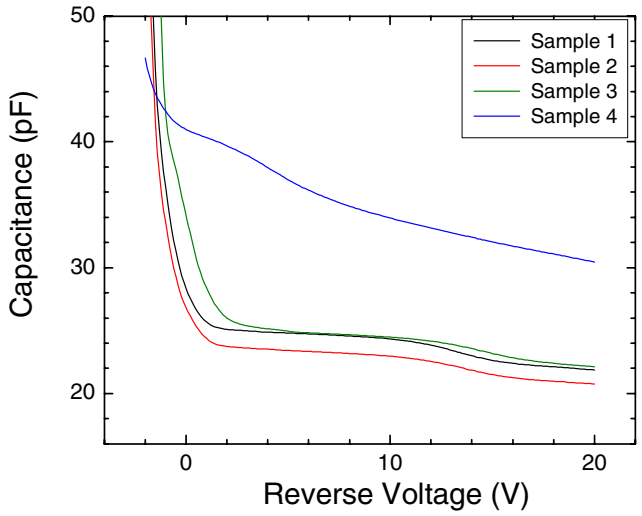

Figure 1 Room temperature capacitance-voltage characteristics in some green LED-type structures.

where A is the active area of the junction mesa, $\varepsilon_r = 8.9$ is the relative static dielectric constant of GaN. Together with charge $Q = \int CdU = \int NeAdx$ (voltage U, electron charge e) we obtain the well-known relations for free carrier density N as a function of depletion width x:

$$x = \varepsilon_0 \varepsilon_r \frac{A}{C} \tag{2}$$

$$n(x) = -\frac{dU}{dC}\frac{C^3}{\varepsilon_0 \varepsilon_r A^2 e} \tag{3}$$

Depletion will occur on both plates of the so-formed capacitor and the depletion width x is the sum of contributions x_a and x_b on both ends, $x = x_a + x_b$. Accordingly, $n(x)$ is a weighted carrier concentration averaging concentrations n_a and n_b on either side. Under realistic conditions, one concentration will dominate, e.g., $n_b >> n_a$, and depletion into region a will dominate: $x \approx x_a$, $n(x) \approx n_a$. In a realistic structure, the charge concentration may vary significantly with depth on both, n- and p-sides of the junction. In particular, a four layer system comprising n-GaN, active region, p-AlGaN and p-GaN layers with a pn-junction at the interface of active region and p-AlGaN might hold the following free carrier concentrations:
$n_{n-GaN} > p_{p-GaN} > p_{p-AlGaN} > n_{active\_region}$.

In this case, starting from forward injection condition towards reverse bias condition, depletion would first dominate in the active region. Upon reaching the interface of n-GaN and active region, depletion would continue with the p-AlGaN layer, which has the next higher density of charges. After full depletion of the p-AlGaN layer, predominant depletion would continue with the p-GaN layer. Along this sequence, charge densities of alternating sides of the original pn-junction would be profiled. The ordinate x of the total depletion width therefore represents the thickness sum of successively depleted layers with increasing carrier concentrations.

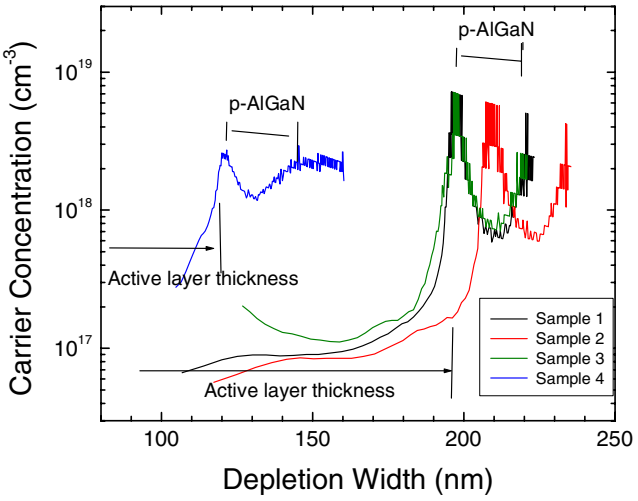

Figure 2 Calculated mobile carrier concentration versus depletion width.

Interpretation of the experimental data along equations (1) - (3) is presented in Fig. 2 for four different dies of slightly different structure. In all cases, with increasing convoluted depletion width *x*, the interpreted carrier concentration raises from values of 10^{17} cm^{-3} to narrow spikes with values of ~ 3×10^{18} cm^{-3}. From there on, the concentration falls to values near ~ 5×10^{17} cm^{-3} before it reaches another high point with values near ~ 2×10^{18} cm^{-3}.
The peak positions on the convoluted depletion width axis for both maxima for some 22 samples are collected and analyzed in the following figures. Fig. 3 correlates the absolute position of the first peak with the total thickness of the nominally undoped active region comprising wells, barriers, and spacer as derived from the x-ray diffraction analysis. As an additional function, a line of slope 1 through the origin is shown. Within the large experimental data set, there is an excellent correlation between both quantities. This suggests that the first peak in the free carrier concentrations marks the completed depletion of the nominally undoped active region. This region is surrounded by the p-type AlGaN electron blocking layer and the highly n-type GaN contact layer.

The experimental spacing between the first and the second maximum for some 25 analyzed samples is shown in Fig. 4 together with the thickness of the AlGaN electron blocking layer as determined from the x-ray diffraction data. To guide the eye, a line of slope 1 through the origin is also shown. Within the large set of data there is a rather good correlation of both quantities. This strongly suggests that the separation of both concentration maxima indeed is the thickness of the AlGaN electron blocking layer. While placing the assignment solely on the data in Fig. 4, would not be very convincing, the fact that one side of the electron blocking layer lies very close to the expected separation from the pn-junction is strong supplementary evidence. The free carrier concentration value in the high 10^{17} cm^{-3} should be an indication of its free hole concentration. Reliable data beyond the second peak could so far not be obtained. It therefore is not possible to identify which layer is being depleted next. This can either be the GaN p-contact layer or the GaN n-contact layer. The above association of depleted layers is indicated by labels in Fig. 2.

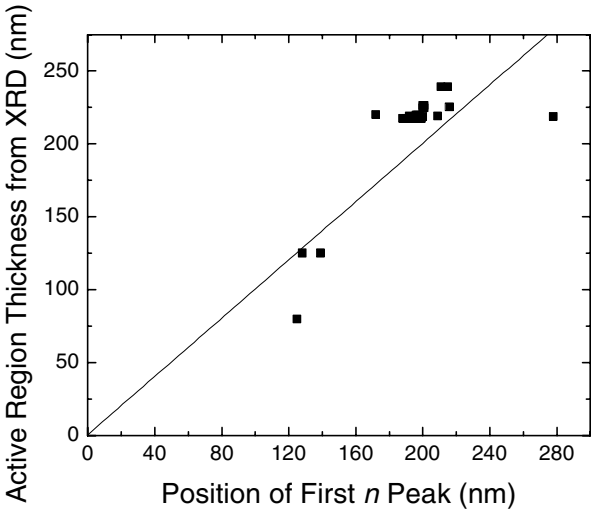

Figure 3 Thickness of the active region derived from $n(x)$ versus that from XRD.

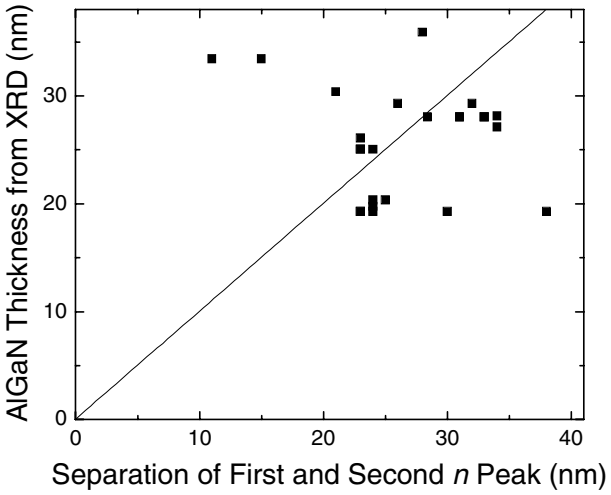

Figure 4 Thickness of the AlGaN electron blocking layer derived from $n(x)$ versus that from XRD.

Detailed analysis of C-V profiles across heterointerfaces has been developed by Kroemer et al. [6]. According to their findings, the first momentum of the excess free charge density around the interface is a measure of the potential drop at the interface and can be related to the relative band offset. An analysis of our data results in values within the reasonable range of 80 – 300 meV. A more accurate interpretation in our case is not possible due to inaccurate knowledge of dopant concentrations typical for group-III nitride heterostructures and the higher complexity of our structures.

In the simplified case of a GaN/GaInN/GaN double heterostructure, Zhang et al [7] propose a correlation of the measured free charge density in the maxima of $n(x)$ with the fixed polarization charge at the heterointerface. In their case, the locally measured free charge density $n(x)$ that exceeds the local concentration of ionized dopants should compensate the fixed polarization charges at one of the interfaces. The total excess free charge under the maximum therefore should be a direct measure of the interface polarization charges. Despite entirely different structures, we obtain values of the same order of 10^{12} cm^{-2} in our experiments. In our case, these values should correspond to the polarization at the GaN/AlGaN heterointerface between the last barrier of the active region and the electron blocking layer.

CONCLUSIONS

In summary, we investigated C-V characteristics of the carrier injection layers of LED-type AlGaInN MQW structures. We propose that derived narrow free carrier maxima indicate the step-wise depletion of active region and the electron blocking layer when the applied voltage is swept from forward to reverse bias. In this way, we directly determine the thickness of the active region and the presence and approximate thickness of the electron blocking layer. The data derived in standard C-V measurement correlates closely with data from x-ray diffraction measurements and the designed structure. Together with a previous detailed analysis of the active region in LED-type GaInN/GaN heterostructures, this identification and quantification of the AlGaN electron blocking layer in convenient capacitance – voltage charge profiling provides a most suitable handle for the fast and reliable LED device characterization and optimization. Step-by-step we are developing the tools to analyze the entire device structure and the exact location of the pn-junction. It therefore should prove suitable for rapid advancement of group-III nitride LED technology for all solid state lighting.

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