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Investigation of electron energy states in InGaN/GaN multiple quantum wells

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ABSTRACT

Blue light emitting diodes (LED) consisting of InGaN/GaN multiple quantum wells (MQWs) have been grown by metal organic chemical vapor deposition (MOCVD) on sapphire. The width of the quantum wells (InGaN) was maintained in the range of 3–5 nm with a barrier of 10–15 nm of GaN. Various diagnostic techniques were employed for the characterization of the InGaN/GaN heterostructure. Carrier concentration depth profile from *C–V* measurements demonstrated the presence of MQWs. The higher value of built-in voltage (15 V) determined from C^{-2}–V plot also supported the presence of MQWs as assumed to alter the space-charge region width and hence the intercept voltage. Arrhenius plots due to DLTS spectra from the device revealed at least four energy states (eV) 0.1, 0.12, 0.15 and 0.17, respectively in the quantum wells, with respect to the barrier. Further the photoluminescence spectrum showed an InGaN-based broad band centered at 2.9 eV and the GaN peak at 3.4 eV. A comparison of the PL spectrum with the literature helped to estimate the indium content in the QW (InGaN) and its width to be ~13% and ~3 nm, respectively. The results were consistent with the DLTS findings.

1. Introduction

InGaN/GaN heterostructures have potential applications in blue/green light emitting diodes and laser diodes because the band gap can be tailored to cover the entire visible and ultraviolet spectra by changing the indium (In) content [1]. The indium content plays a critical role in achieving a strong band-to-band emission [2]. But the radiative efficiency is decreased due to the presence of deep level defects in multiple quantum wells (MQWs) that can act as nonradiative recombination centers [3]. Despite much research on the properties of InGaN/GaN quantum wells (QWs), the impact of the deep level defects on the efficiency of the device is still not well understood. Therefore a detailed study will be helpful to comprehend the deep level defects in InGaN/GaN multiple quantum wells. Several techniques have been employed to characterize these states in multiple quantum wells such current–voltage measurements (*I–V*) [4], capacitance–voltage (*C–V*) measurements [5], Photoluminescence spectroscopy (PL) [6] and deep level transient spectroscopy (DLTS) [7]. Among them, DLTS is very efficient and powerful tool for detection and characterization of electrically active deep levels [8]. In a quantum well structure, the emission and capture of carriers confined in the well regions behave similarly to the emission and capture of carriers by the deep level defects [9–11].

In this study, we have investigated the deep level defects of InGaN/GaN quantum wells with a metal-semiconductor diode structure by performing *I–V*, *C–V* and DLTS measurements. Four electron energy states were observed in QWs having activation energies to be 0.1, 0.12, 0.15 and 0.17 eV. In the following, we will describe experimental, results and discussion and conclusion in Sections 1–3, respectively.

2. Experimental

The samples were grown by metalorganic chemical vapor deposition (MOCVD) technique in a modified D125 Emcore reactor on 2-inch sapphire wafers with 2 μm GaN template layers. The precursors for Ga, N and In were trimethylgallium (TMGa), ammonia (NH_3) and trimethylindium (Cp3Gd), respectively. InGaN/GaN quantum wells of 3–5 nm well width with 10–15 nm barriers were produced. For DLTS measurements, photolithographically defined Ti (50 nm)/Au (200 nm) contacts with an area $\sim 1.34 \times 10^{-4}$ cm^2 were fabricated on the device structures. The InGaN/GaN quantum wells were characterized using DLTS and PL spectroscopy. The DLTS was carried out over a temperature range of 80 to 350 K and the PL was excited at room temperature using the 325 nm line of a 5 mW He–Cd CW laser and analyzed with a Horiba UV-spectrometer.

3. Results and discussion

3.1. I–V measurements

Fig. 1 displays the typical *I–V* behavior obtained from an InGaN/GaN MQW LED. The light emission is turned on at voltage

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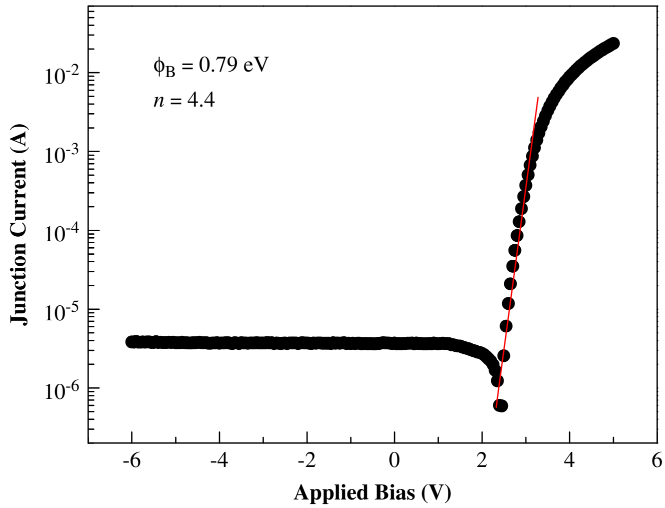

Fig. 1. *I–V* curve of the MQW-InGaN/GaN blue LED. The large ideality factor (4.4) demonstrates that the conduction mechanism is tunneling [15].

2.25 V showing the forward current to be 2 mA, which approaches to 200 mA at 2.5 V. The current value is smaller than that reported by others [12,13] probably due to larger carrier recombination rate to be discussed later. Series resistance obtained from the forward biased *I–V* curve is 45 Ω. The *I–V* characteristics of LED is represented by the following relation [14]:

$$I = I_S\left[\exp\left(\frac{qV}{nkT}\right)-1\right] \tag{1}$$

where n is the ideality factor, and I_S the reverse saturation current of the device, is given by

$$I_S = AA^*T^2 \exp\left[\frac{-q\phi_B}{kT}\right] \tag{2}$$

All the parameters in the above equations bear usual meanings [14,30]. The log of the *I–V* curve yields an ideality factor n of the device. The measured value of the ideality factor is 4.4, showing that the conduction mechanism in an InGaN/GaN LED is most probably dominated by tunneling [15], which supports the presence of quantum wells. The activation energy is calculated from the relation $E=nkT$, $T=300$ K and, is found to be 0.1 eV. This result is in agreement with the literature [16,17].

3.2. C–V measurements

C–V measurements were performed for the investigation of the quantum wells' electronic properties and free carrier concentration profile in the device [18,19]. Fig. 2 demonstrates a depth profile of free carrier concentration in InGaN/GaN quantum wells at 300 K. The concentration peak confirmed the presence of quantum wells, i.e. a confinement of electrons in quantum wells. It is important to notice here that the relatively high concentration of free carriers ($>1.0\times10^{19}$ cm^{-3}) in the device could only allow the depletion of the carriers only ~13 nm away from the built-in depletion region of ~12 nm. The built-in potential was determined from the intercept of the C^{-2}–V plot, which is about 15 V. The observation of high values of built-in-potential due to the MQW active region is commonly reported in the literature.

3.3. DLTS measurements

Information from *C–V* profiling is important when performing DLTS characterization. Among the measuring parameters of DLTS,

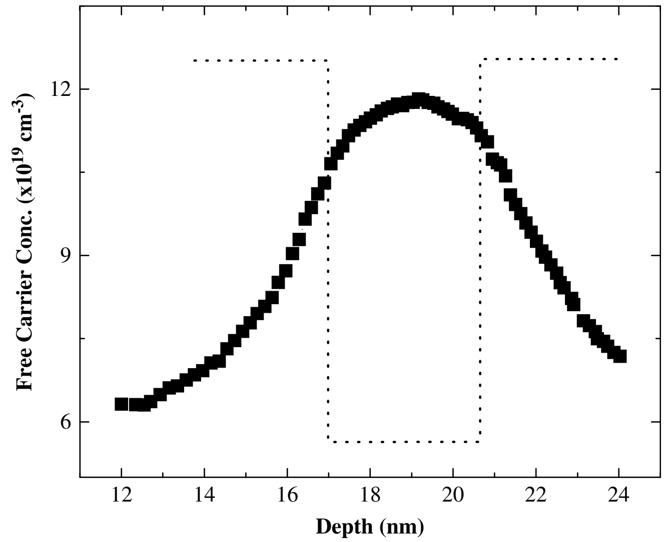

Fig. 2. Demonstration of accumulation of carriers in quantum well (GaN/InGaN/GaN) of about width 3 nm, from *C–V* profiling. Symbols and dotted line represent measured data and a probable quantum well position.

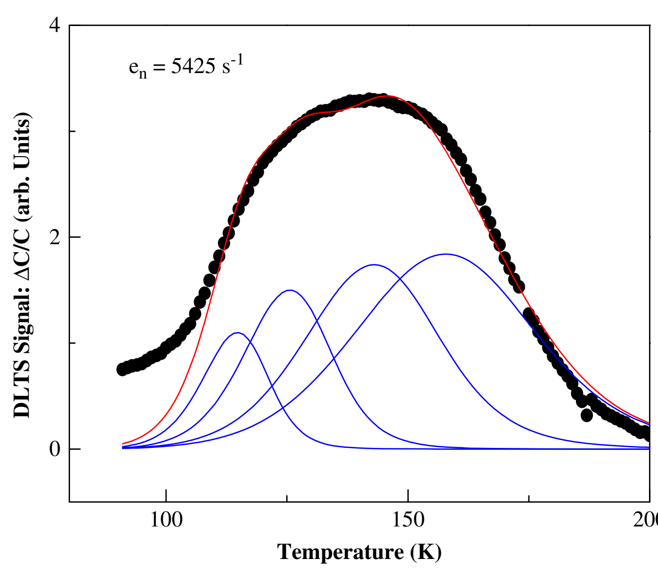

Fig. 3. A multiple peak fitting of DLTS spectrum measured at $V_R=-7$ V, $V_p=0$ V, $t_p=20$ μs (i.e. a larger profiling region) displays that the measured DLTS signal (symbols) is composed of four energy levels in the quantum well [27].

reverse bias level and filling pulse are significant. These determine the region of the junction where the electron occupation of deep levels is varied [20] and, therefore, the region from which the emission of carriers is observed. The possibility of tuning the junction region probed by DLTS is particularly useful in experiments involving semiconductor heterostructures [21–24]. Fig. 3 displays the DLTS spectra of electron energy levels in a quantum well. The measurements were performed with a lock-in frequency set at 2500 Hz, reverse bias of $Ur=-5$ V, pulse bias $U_1=5$ V (with respect to the reverse bias), pulse duration of $t_p=20$ μs. Before we discuss the DLTS data of our device, it is not out place to refer Song et al. [25] finding where they suggested that in the quantum well structures, the thermal activation energy obtained from emission rate can be used to measure the energy separation between the localized confined states in a quantum well structure