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Trap Characterization of InGaN/GaN Blue Light Emitting Diode Grown on Si Substrate

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Abstract: Three hole traps and one electron trap were revealed for InGaN/GaN blue LEDs grown on Si by a combination of DLTS and ICTS. Time-resolved thermal-enhanced emission process of deep hole trap was investigated.

1. Introduction

III-nitride based light emitting diodes (LEDs) grown on Si substrates have been regarded as a viable solution for low-cost illumination, solid-state lighting, and so on [1, 2]. Despite large lattice and thermal mismatches between GaN and Si, there has been dramatic progress in improving the light output power and reliability of III-N LEDs on Si. Recently, there is an increasing interest in utilizing III-N LEDs for micro-pixelated display and visible light communications. Towards high-speed response and large data transmission rate, it is demanding to understand the behaviors of the carrier traps, particularly those inside the active region, i.e., multi-quantum well/barrier layers. There have been some prior works attempting to investigate deep-level defects of LEDs grown on sapphire substrates [3, 4], however, there has been little study focusing on trap properties of III-N LEDs grown on Si substrates [5]. In this work, electrical and trap properties were explicitly investigated for InGaN/GaN blue LEDs grown and fabricated on Si. Two hole traps and one electron trap were extracted using Deep Level Transient Spectroscopy (DLTS) [6]. Moreover, the temperature-dependent emission time constant (τ) of hole trap H3 was also discussed by Isothermal Capacitance Transient Spectroscopy (ICTS) [7].

2. Device Structure and Electrical Characterizations

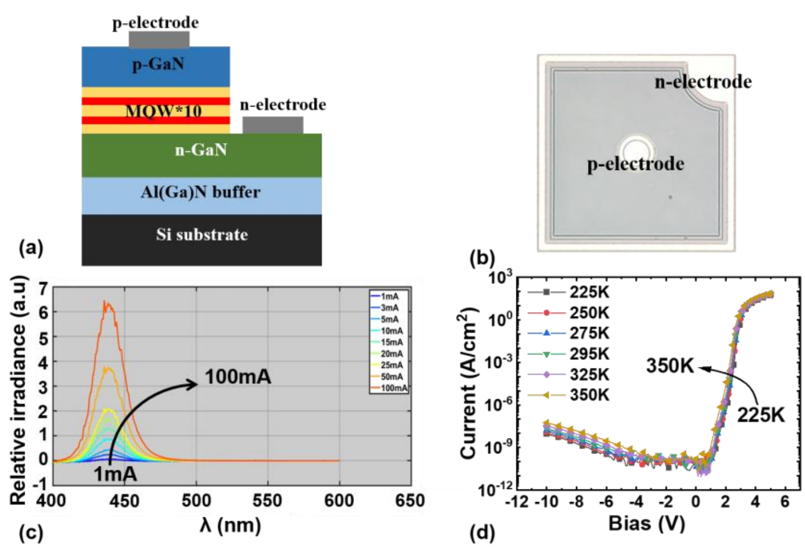

Fig. 1. (a) Schematic of blue LED on Si. (b) Optical image of blue LED. (c) The electroluminescence (EL) curves. (d) The I-V characteristics at different temperatures.

Fig. 1(a) shows the schematic of blue LED grown and fabricated on a Si substrate. From the Si substrate to the top surface, the LED structure consisted of a thin nucleation layer, a AlGaN buffer layer, a 2-µm-thick Si-doped n-GaN layer, ten periods of InGaN/GaN QWs, and a 200-nm-thick Mg-doped p-GaN layer.

The electroluminescence (EL) spectra of the LEDs on silicon are shown in Fig. 1(c). With an injection current of 20 mA, the light output power of the LEDs on Si (without package) was measured to be 3.25 mW. With increasing the injection current from 1 mA to 100 mA, the peak of electroluminescence curves was consistently measured at 443.6 nm. Fig. 1(d) shows the I-V characteristics of a fabricated LED from 225 K to 350 K. At -10 V, the leakage current density was decreased from 5.58×10^{-8} A/cm^2 to 9.20×10^{-9} A/cm^2 with decreasing temperature from 350 K to 225 K.

3. Deep-Level Characterization

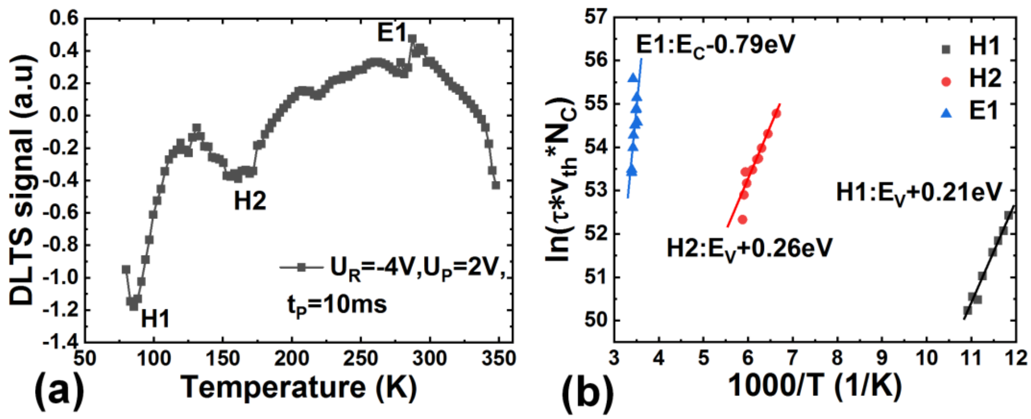

Fig. 2. (a) Temperature-scanning DLTS spectra from 80 K to 350 K at 1MHz. (b) Arrhenius plot of two hole traps and one electron trap labeled as H1, H2 and E1, respectively.

Figure. 2(a) shows the DLTS signal spectra scanned from 80 K to 350 K with a reverse bias U_R=−4 V, a filling pulse U_P =2 V, and a filling pulse width t_P=10 ms. The DLTS signal revealed two hole traps H1, H2 with activation energy of 0.21 eV and 0.26 eV, and one electron trap E1 with an activation energy of 0.79 eV, as shown in Arrhenius plot [Fig. 2(b)] and Table 1. The electron trap E1 (E_A=0.79 eV) is widely observed and reported in (In,Ga)N/GaN nanowire (E_C-0.84 eV) [8] and InGaN QW of the near-UV LEDs [9]. This trap is believed to be associated with nitrogen interstitial-related defects (E_C-0.8 eV). The H1 trap matches the one (E_A=0.19 eV) reported by low frequency noise measurement [10] well, which has a much higher trap density. The trap concentration (N_T) of H1 is the highest among the three traps revealed in this study. The H2 has a similar energy level with the hole trap in deep ultraviolet (DUV) LED [11].

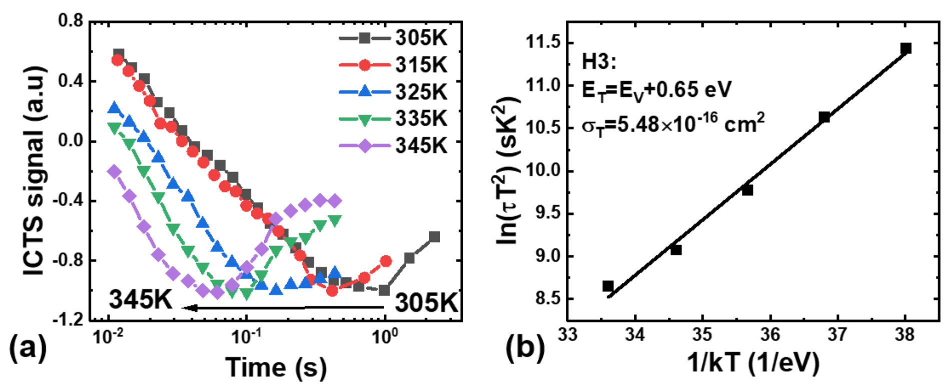

Fig .3. (a) ICTS signals scanned from 305 K to 345 K. (b) The Arrhenius plot of deep hole trap known as H3.

Isothermal Capacitance Transient Spectroscopy (ICTS) was utilized to examine the time-resolved emission process of the blue LED. At five fixed temperatures from 305 K to 345 K, normalized ICTS signals as a function of time are shown in Fig. 3(a). Emission time constant τ can be extracted by identifying the valley positions of each temperature. As increasing the temperature, τ decreases from 0.99 s at 305 K to 48 ms at 345 K, which indicates that the emission process is accelerated by the temperature.

Based on the temperature-dependent time constant, one may extract the activation energy of the trap via the equation below [6]:

$$\ln(\tau T^2)=\frac{E_T\text{-}E_V}{kT}-\ln(\gamma\sigma_T) \tag{1}$$

where E_T, E_V and k denote the deep trap level, the top of the valence band, and Boltzmann constant respectively. The emission time constant and temperature product were used to construct the Arrhenius plot in Fig. 3(b). The activation energy of this trap (E_T-E_V) was extracted to be 0.65 eV and labeled as H3. It is noted that this trap was not revealed by the temperature-scanning mode DLTS [Fig.2] due to limited temperature range, however, can be identified by the ICTS. The H3 shares the same activation energy as the trap detected by optical DLTS in blue LEDs, which has a comparable capture cross section [12].

Table 1. Properties of traps extracted from DLTS and ICTS.

Trap No.	Activation energy (eV)	Capture cross section (cm^2)	N_T $\times 10^{13}$ (/cm^3)
E1	E_C-0.79	1.38×10^{-10}	3.22
H1	E_V+0.21	5.28×10^{-11}	15.4
H2	E_V+0.26	8.29×10^{-16}	2.04
H3	E_V+0.65	5.48×10^{-16}	-

4. Conclusion

In our study, the device performance and trap characteristics of blue LEDs on Si have been investigated for a wide temperature range from 80 K to 350 K. Three hole traps (H1, H2, and H3) and one electron trap (E1) were extracted by a combination of DLTS and ICTS. In addition to activation energy and capture cross section, the thermal-enhanced emission process of hole trap (H3) was studied by ICTS from 305 K to 345 K.

5. Acknowledge

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