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Influence of constant current stress on the conduction mechanisms of reverse leakage current in UV-A light emitting diodes

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ABSTRACT

The influence of constant current stress on the conduction mechanism of reverse leakage current in ultraviolet (UV) light emitting diodes (LEDs) in the UV-A spectral range has been investigated for the first time using temperature-dependent current-voltage measurement from 370 K to 55 K. Below 220 K, variable range hopping mechanism dominates in UV-A LEDs. While, above 220 K, the leakage current is attributed to Poole-Frenkel emission mechanism within the bias range of −3 ~ −6 V. With the increasing of the reverse bias, the conduction mechanism transforms from Poole-Frenkel emission to space-charge-limited conduction mechanism. In particular, applying electrical stress yields an alteration of the transition voltage from −7.5 V to −6.5 V. We propose that stress could lead to a reduction of the thermal activation energy, and therefore alters the transition voltage.

1. Introduction

Due to the great advantages, ultraviolet (UV) light emitting diodes (LEDs) in the UV-A spectral range have attracted a great interest, such as counterfeit banknote detection, white light illumination, water treatment and so on [1–8]. However, the further understanding on the reliability of UV-A LEDs, which is a bottleneck to hinder their wide applications, is still lacking, even though the performance of them is becoming better and they are gradually used in above applications. Among those reliability issues, studying the reverse leakage current is usually much important, because it has a significant effect on the performance of the devices, such as optical power, lifetime, the ability of electronic discharge resilience, etc. [9–13]. Therefore, understanding the conduction mechanisms of reverse leakage current is becoming a pressing issue for UV-A LEDs nowadays.

Furthermore, it is known that the device degrades severely within a long period operation, during which the reverse leakage current increase significantly as well [14]. Thus, mechanisms of degradation by electrical stress should be equally focused, in addition to the device fabrication and application [15,16]. However, the effect of electrical stress on the reverse

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leakage current from view of conduction mechanism has not been investigated to the best of our knowledge. Consequently, studying the conduction mechanisms with consideration of the electrical stress becomes essential.

In this paper, the effect of electrical stress on the conduction mechanisms of reverse leakage current in UV-A LEDs has been investigated, with the aid of temperature-dependent current-voltage (I-V-T) measurement. It is found that both temperature and bias can lead to the variation of the conduction mechanism of reverse leakage current. Furthermore, the transition voltage of conduction mechanism becomes lower after electrical stress, and we put forward that this phenomenon is highly related to the variation of thermal activation energy.

2. Experimental

UV-A LED wafers were prepared on (0001) sapphire substrate using metalorganic chemical vapor deposition (MOCVD). Apart from the substrate, a 1-μm-thick undoped GaN buffer, a 900-nm-thick Si-doped n-type GaN layer (doping concentration $N_D = 5 \times 10^{18}$ cm^{-3}), a multiple quantum wells (MQWs) active layer, a 20-nm-thick Mg-doped $Al_{0.16}Ga_{0.84}N$ electron blocking layer, and a 220-nm-thick Mg-doped p-type GaN layer (doping concentration $N_A = 10^{20}$ cm^{-3}) were grown from bottom to top, respectively. The active layer consisted of eight 1-nm-thick InGaN quantum wells (QWs) separated by nine 10-nm-thick GaN barriers. The indium composition was set to be 9%. The final UV-A LEDs were obtained after deposition of Ti/Al/Ni/Au and Ni/Au metal electrodes used for n-Ohmic and p-Ohmic contact metals, respectively. The chip size was 1143 μm × 1143 μm, and the wavelength is 390 nm at 300 K.

I-V-T measurements are effectively and commonly used to characteristic the conduction mechanisms of reverse leakage current in UV-A LEDs, and were carried out here using Semetrol I-V-T system on the same device before and after the constant current stress, respectively. In order to avoid the potential damage on the device, the maximal reverse bias was set as −10 V. Moreover, the temperature range was also considerately selected from 370 K to 55 K, which is safe for the device measurement. Besides, a constant current of 450 mA was applied to the device during the stress experiment, which is above the limitation of operation current and can cause evident degradation.

3. Results and discussion

The reverse current-voltage (*I-V*) characteristic during the electrical stress at 300 K in the UV-A LED is shown in Fig. 1. It is clearly observed that the reverse leakage current increases significantly with the increasing stress time, which denotes a severe degradation of the device. Thus, it is necessary to deeply understand the conduction mechanisms of reverse leakage current in UV-A LEDs, especially the influence of stress on it.

In order to investigate the conduction mechanisms, the reverse leakage currents before and after stress are plotted as a function of reciprocal temperature. As shown in Fig. 2, the datum of the Arrhenius plot are measured at −6 V, and two distinct regions of the curves appear obviously in this plot, which illuminate that the conduction mechanisms in these two regions are different.

As for data below 220 K, the temperature dependence of the reverse leakage current can be explained by variable range hopping (VRH) mechanism. It is known that the relation between VRH current and temperature can be explained as follow [17–20]:

$$I \propto I_0 exp\left\{ -\left(\frac{T_0}{T}\right)^{\frac{1}{4}} \right\}, \quad (1)$$

where T_0 is the characteristic temperature. As shown in Fig. 2, the measured datum before and after stress are fitted according to eq. (1), respectively. A good agreement is observed, and the characteristic temperatures T_0 before and after stress are extracted, which are 1.66×10^4 K and 2.63×10^5 K, respectively. In comparison with the results in Refs. [17,21], they are reasonable values. And, it should notice that this phenomenon was also found in other nitride based LEDs, i.e. VRH is found to be the dominant mechanism of InGaN/GaN LEDs in the low temperature range [11]. Therefore, it is concluded that the conduction mechanism before and after stress in UV-A LEDs below 220 K is dominated by VRH process. Besides, under other bias within the range of −3 ~ −10 V, the phenomenon is consistent. Consequently, electrical stress does not have an effect on the conduction mechanisms of reverse leakage current below 220 K.

Then, the conduction mechanisms of reverse leakage current is studied above 220 K, which is the typical range for UV-A LEDs operation. As shown in Fig. 2, a rapid increase of reverse leakage current can be observed above 220 K, and we found that VRH model can no longer fit the experimental data well for both fresh and stressed device, which indicates that the conduction mechanism is changed. It is found that, the leakage current decreases exponentially with the increasing of *1/T*. This behavior usually denotes the appearance of another process, the Poole–Frenkel (PF) emission mechanism, which can be expressed by the following equations [22–24]:

$$I \propto exp\left\{ -\frac{E_a}{kT} \right\}, \quad (2)$$