Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp226-227

# Elucidating the electrical characteristics of an inversion domain boundary in p-type GaN of light-emitting diodes

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## 1. Introduction

Nitride-based materials have been used in the recent decade in a wide range of optoelectronic devices such as light emitting diodes (LEDs) and laser diodes (LDs) [1]. In this field, magnesium (Mg) is most commonly used as a *p*-type dopant for these materials. However, its large ionization energy (~120-200meV) explains why its hole concentration is significantly lower than its Mg concentration [2]. Therefore, the hole concentration in *p*-GaN is limited, causing difficulties in making ohmic contacts and a low resistance in *p*-type GaN. Additionally, increasing the Mg doping concentration in *p*-type GaN incurs heavy doping effects such as impurity scattering and self-compensation. Many studies confer that such effects cause poor conductivity in *p*-type GaN, subsequently degenerating the electrical characteristics of LEDs. Moreover, a planar defect that is identified as a horizontal type inversion domain boundary (IDB) is frequently observed at *p*-type GaN with a high Mg-doped concentration by using transmission electron microscopy (TEM). An IDB originates from pyramidal defects that are attributed to the stacking faults; at this boundary, the polarity of films is inverted from Ga-face to N-face [3]. Based on this feature, IDB is promising for use in devices that can control the polarity. Additionally, M. Stutzmann *et al.* [4] found that an IDB between Ga-face and N-face regions functions as a rectifying junction due to the existence of opposite-polarity regions in this material, and is promising for use in novel applications. Despite the numerous of investigations on the formation of IDBs, the electrical characteristics of IDBs remain unclear, necessitating an investigation of how the electrical characteristics affect LEDs with an IDB in *p*-type GaN.

This study investigates three LEDs with varying Mg concentrations in *p*-GaN by using TEM. Exactly how the IDB affects the electrical characteristics is studied by using capacitance-voltage (*C-V*) measurements and current-voltage *(I-V*), respectively.

## 2. Experimental procedure

Three samples in this study were grown on *c*-plane sapphire substrates by low-pressure metal-organic chemical vapor deposition (MOCVD) in a vertical Thomas Swan system. A 20nm thick GaN nucleation layer was grown at 620°C. A 0.5μm thick undoped buffer layer and a 3μm thick Si-doped *n*-type GaN layer were then grown at 1200°C, respectively. Next, 9 periods of multiple quantum wells (MQWs) were deposited with each period and consisted of a 2nm thick InGaN well grown at 885°C and an 8nm thick GaN barrier with Si-doped grown at 990°C. Additionally, a 0.2μm thick *p*-type GaN was deposited at 1060°C. Finally, an extremely thin InGaN contact layer was grown on top of the surface at 900°C to fabricate p-type ohmic contacts. For the three samples, the flow rates of bis-cyclopentadienyl magnesium ($Cp_2Mg$) in *p*-type GaN layer were 0.004, 0.008 and 0.016 μmole/min, respectively. The formation of an IDB and its surface morphology was determined by cross-sectional TEM and plane-view scanning electron microscopy (SEM), respectively. For electrical measurements, the samples were processed to standard 180×235μm$^2$ LEDs following crystalline growth.

## 3. Results and discussion

A cross-sectional TEM image of a dark line in p-type layer was exhibited for the highest flow ratio (Fig. 1(a)), but did not appear in other samples. High-magnification of TEM images of the dark line was formed by a pyramidal interface (Fig. 1(b)). Many investigations have observed a similar phenomenon, in which the pyramidal interface was considered to be an IDB. IDB has been proposed for many explanations, which induced polarity inversion from Ga-face to N-face (Fig. 2).

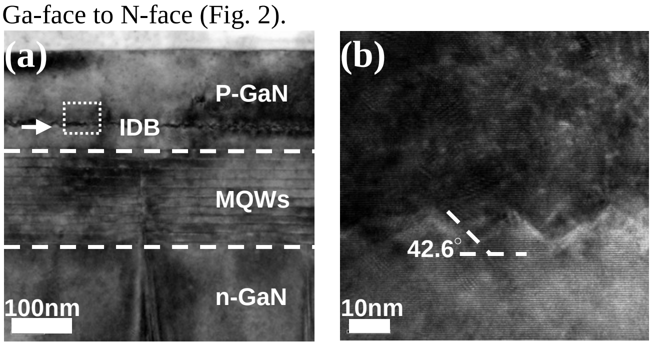


Fig. 1 (a) Cross-sectional TEM image of LED with 0.016 flow ratio. (b) High-magnification TEM image of pyramidal interface in p-layer.

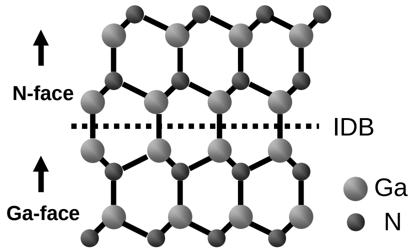


Fig. 2 Schematic of inversion domain boundary (IDB).

This study also investigated the electrical properties of the samples. Figure 3(a) shows the *C-V* characteristics of the samples. According to Fig. 3(b), the apparent carrier concentration profiles can be obtained. Since the barriers of the MQWs are Si-doped, carriers that accumulated in the wells can be swept out when the depletion region reaches them; in addition, peaks of the curve that describe the accumulated carriers in wells can be observed [5]. However, the depth profile in the heaviest Mg-doped sample significantly differs, in which only two peaks are observed in the profile and the apparent carrier concentration decreases with the depletion region. Since the Si-doped concentrations of the samples are the same, the decrease of the apparent carrier concentration can be attributed to the extension of the depletion region to the p-GaN region. In this study, when the depletion region expands to the IDB region,

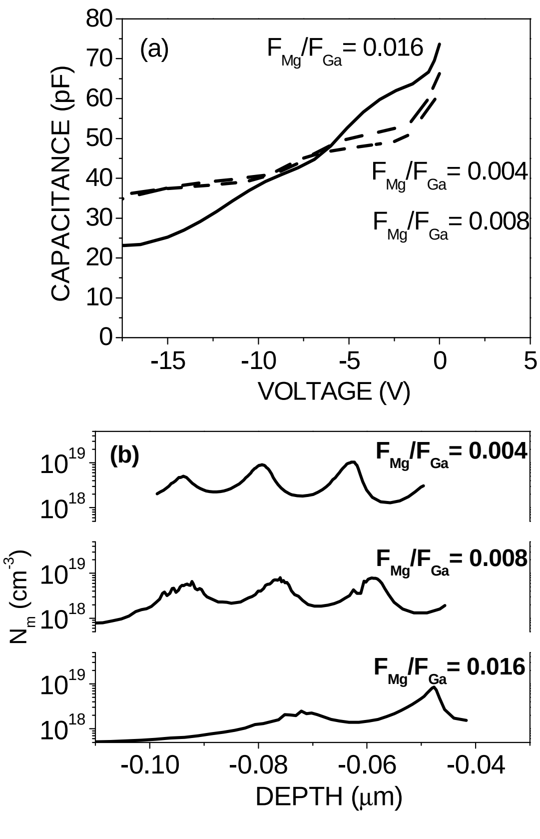


Fig. 3 (a) *C-V* curves of samples for the flow ratio of p-type layer with 0.004, 0.008, and 0.016, respectively. (b) Depth profiles of the apparent carrier distribution obtained from (a).

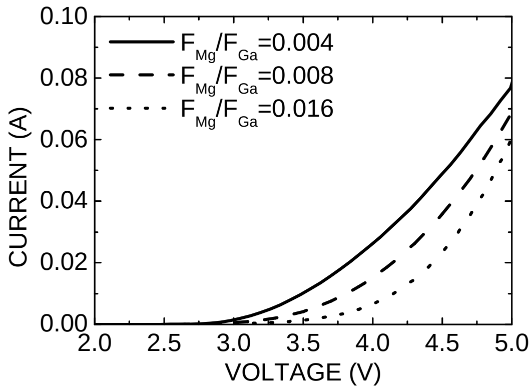


Fig. 4 *I-V* curves of samples for the flow ratio of p-type layer with 0.004, 0.008, and 0.016, respectively.

the apparent carrier concentration is reduced. This phenomenon suggests that the IDB reduces the carrier concentration, as explained by the existence of opposite-polarity in this region. Thus, the compensating charges in this region are depleted, creating a local potential to oppose the current flow which functions as a rectifying junction. Moreover, according to *I-V* measurements, the forward voltage (VF) increases with the Mg-doped concentration (Fig. 4). This phenomenon is attributed to the heavy doping effects, including self-compensation and the formation of an IDB.

## 4. Conclusions

This study investigated three nitride-based LEDs with varying Mg-doped concentrations of *p*-type layer. An IDB was observed in the sample of the highest Mg-doped concentration. The depth profiles of apparent carrier density based on *C-V* measurements indicated that the carrier concentration in the IDB region reduces rapidly. This reduction could be attributed to the self-formation of a rectifying junction in the IDB region resulting from its opposite-polarity in this boundary, ultimately increasing the operating voltage of the device.

## Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research. Ted Knoy is appreciated for his editorial assistance.

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