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Effects of V-pits covering layer position on the optoelectronic performance of InGaN green LEDs

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Abstract: The impact of the V-pits covering layer (VCL) position on the optoelectronic performance of InGaN-based green light-emitting diodes (LEDs) was investigated. It is found that earlier covering of V-pits will hinder the hole injection via the sidewall of V-pits, and then result in less quantum wells (QWs) participating in radioluminescence. The current-voltage characteristics show that the LEDs with earlier covering of V-pits have higher operating voltage at room temperature, and a more dramatic voltage rise with the reduction of temperature. Meanwhile, more manifested emission peaks for sidewall QWs and deeper QWs near to n-type layer was observed in the sample with earlier coveing of V-pits at cryogenic temperatures, for the reason that the holes being injected via V-pits sidewall have higher kinetic energy and could transport to deeper QWs.

Key words: green light-emitting diodes; V-pits covering layer; hole injection efficiency; operating voltage

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1. Introduction

GaN, which is an important semiconductor material, and its related alloys (AlInGaN) have recently attracted wide attention[1, 2]. Because of their large bandgap, they are widely used in the fabrication of optoelectronic and electronic devices, such as laser diodes (LDs), light-emitting diodes (LEDs), and high electron mobility transistors (HEMTs)[3, 4]. Due to their unique advantage in terms of environmental benefit and energy savings, the InGaN-based LEDs have been widely investigated and used in various fields, such as solid-state lighting, displays fields, medical instrumentation, and others[4-7]. Various research groups have demonstrated that intentionally introduced V-pits could effectively screen threading dislocations and enhance the optoelectronic properties of AlInGaN-based LEDs[8]. In addition, it has also been observed that the V-pits could promote the injection of holes into quantum wells (QWs) closer to n-GaN, and then influence quantum efficiency[9, 10]. During the epitaxial growth, the average size and density of V-pits can be controlled by adjusting the growth temperature and the periods of InGaN/GaN superlattices (SLs)[11]. The V-pits can be covered by controlling the p-type layer growth condition, such as growth temperature, carrier gas and pressure.

Since these V-pits are generated from the dislocation of stress-release layer, laying through the multi-quantum wells (MQWs) region[12, 13] and then grow upward at a fixed intersection angle (56°)[14], the position of V-pits covering layer (VCL) will directly determine the quantity of p-type layers contained in V-pits. As an effective technique to enhance the performance of LEDs, the effect of V-pits on the optoelectronic performance of LEDs has widely been investigated. However, the impact of the VCL position on the optoelectronic properties of LEDs has only rarely been discussed. In this letter, the optoelectronic performances of InGaN-based LEDs with different position of VCL are investigated. It is found that LEDs with earlier covering of V-pits have higher operating voltage. The position of the VCL can also change the transport paths of holes and then influence the external quantum efficiency (EQE) of LEDs.

2. Experiments

The investigated samples were grown on 2-inch silicon (111) substrates by a Thomas Swan close-coupled showerhead metal organic chemical vapor deposition (MOCVD) system. To investigate the effect of the VCL on the hole injection, we have grown two samples with different position of the VCL. As shown in Fig. 1(a), the epitaxial structure of sample A consists of a 120-nm-thick AlN buffer layer, a 2.8-μm-thick Si-doped (5×10^{18} cm^{-3}) n-GaN, a 32 period superlattice layer, and a 10-nm-thick low-temperature GaN (LT-GaN). The active region consists of two kinds of MQW, the five pairs of QWs closed to the n-type layer were 2.8 nm-InGaN/13 nm-GaN and the five pairs of QWs closed to p-type layer were 2.8 nm-InGaN/10 nm-GaN[15] followed with a p-AlGaN electron blocking layer (EBL), a p-GaN layer, a p-AlGaN/InGaN SL, an unintentional-doped GaN VCL and a p-GaN contact layer. For convenient comparison, the epitaxial structure of sample B is the same as that of sample A except for the position of VCL inserted between the EBL and the p-AlGaN/InGaN SL, as shown in Fig. 1(b). Samples were fabricated as 1 mm^2 vertical LED chips—the detailed fabrication process has previously been reported[16]. The temperature-dependent electroluminescence (EL) of two samples was measured with a CAS140CT spectrometer connected with an IP250 integrating sphere. The temperature controller and 2635A source meter were made by MMR Technologies, Inc., and Keithley Instruments, Inc, respectively[17]. The room temperature dominant wavelength of the

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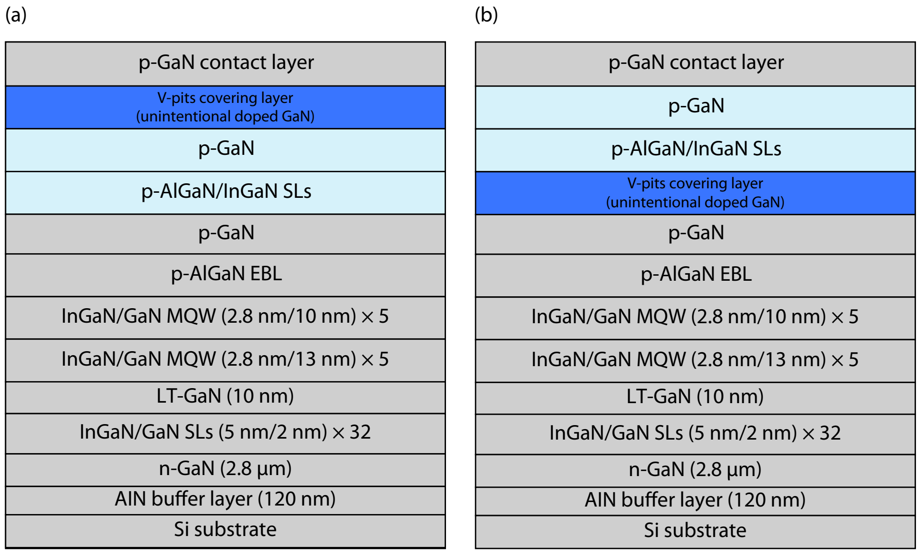

Fig. 1. (Color online) Schematic epitaxial structures of two samples with different position of V-pits covering layer.

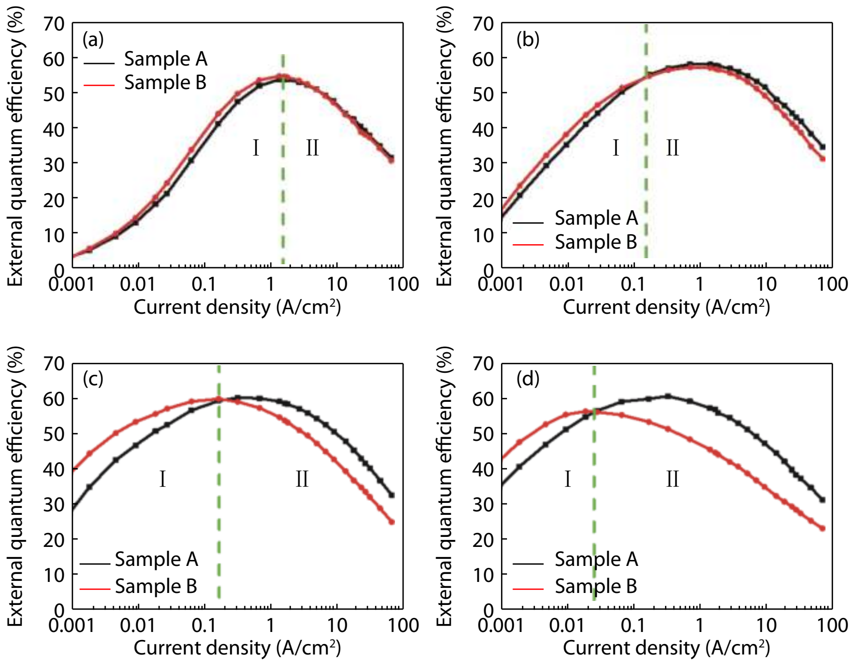

Fig. 2. (Color online) The temperature-dependent EQE as a function of currents at (a) 300 K, (b) 200 K, (c) 150 K, (d) 100 K, respectively.

two samples was both around 525 nm under 35 A/cm^2. The scanning transmission electron microscopy (STEM) data were obtained using a FEI Tecnai TF20 FEG-TEM operated at 200 kV.

3. Results and discussions

The temperature-dependent EQEs as a function of current density are shown in Fig. 2. The EQEs of two samples are almost identical at room temperature. However, when the temperature drops from 300 to100 K, sample B has a higher EQE in region Ⅰ but a lower EQE in region Ⅱ. Since the EQE is mainly influenced by the hole injection efficiency at region Ⅰ[18] and the holes could be transported to the deeper QWs via the sidewall of V-pits[6], the different EQEs between the two samples at region Ⅰ should be caused by the factors related to the hole injection efficiency.

The STEM images of the epitaxial structure with V-pits in two samples are shown in Fig. 3. For convenience, we define the two heavily doped p-GaN layers and the p-AlGaN/InGaN SL in sample A as a hole injection layer (HIL), the single heavily Mg-doped p-GaN layer in sample B as a hole injection layer 1 (HIL1), the p-AlGaN/InGaN SL and another heavily Mg-doped p-GaN layer grown subsequently as a hole injection layer 2 (HIL2). As a result of the different position of VCL, the V-pits in sample A contain the entire HIL grown subsequently, as shown in Fig. 3(a), but only contain a single p-GaN layers in sample B and are then filled with the unintentional-doped VCL, as shown in Fig. 3(b). This means that the hole concentration in V-pits of sample A is higher than that of sample B. Moreover, since the resistivity of the VCL in V-pits is higher than that of the VCL in the c-plane due to the special inverted pyramid structure, the holes in sample B generated from the HIL2 above the V-pits are easier to flow through the c-plane rather than drop directly into the V-pits. The effect of these factors on hole injection efficiency may not obvious at room

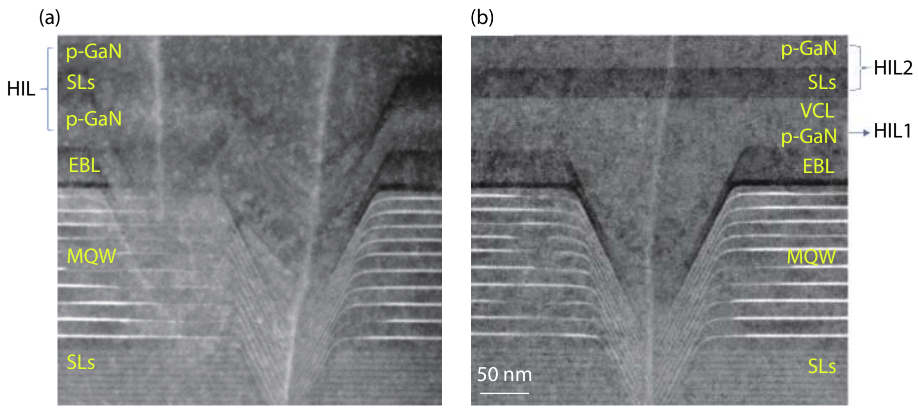

Fig. 3. (Color online) The STEM image of two samples with V-pits structure.

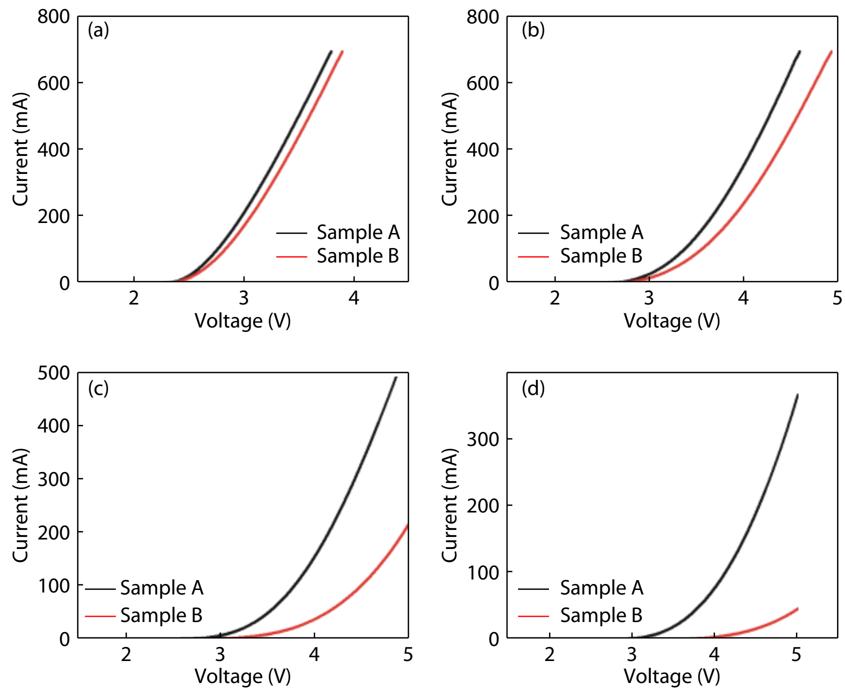

Fig. 4. (Color online) Current–voltage curves in linear scale of two samples at (a) 300 K, (b) 200 K, (c) 150 K, (d) 100 K, respectively.

temperature due the sufficient hole concentration. However, when the hole concentration decreases dramatically due to the acceptors freezing out with temperature decrease[19], the holes in sample A could be transported to deeper QWs via sidewall of V-pits but can only fill up a few QWs near the p-type layer via the *c*-plane in sample B. In the condition of insufficient holes, sample B with less QWs taking part in radioluminescence has a higher carrier density at region Ⅰ and will also be quicker to get to carrier saturation as the injected current increases, which leads to the EQE of sample B being higher at region Ⅰ but drooping earlier at region Ⅱ.

The current–voltage curves of two samples at various temperatures are demonstrated in Fig. 4. Sample B has a higher operating voltage at room temperature and the degree of voltage difference between two samples is amplified with the temperature drop. The V-pits can effectively decrease the operating voltage due to the improved injection of holes via the sidewall of V-pits[20]. Therefore, we surmise that the difference of voltage between two samples should be also correlated with the efficiency of hole injection via the sidewalls of V-pits. As we discussed in Fig. 2, compared to sample B, the holes in sample A are easier to pass through the sidewall of V-pits due to the different epitaxy structure, which can effectively decrease the operating voltage at room temperature. It can also be observed that the increase of the voltage of sample B is much higher than that of sample A as the temperature decreases (especially when the temperature falls below 200 K). Considering that the thickness of epitaxy layer grown on the sidewall of V-pits is about 1/3–1/5 times than those on the *c*-plane, the thickness of HIL in sample A is much thicker than HIL 1 in sample B. Thus, the hole concentration in V-pits of sample B decreases more dramatically when the Mg acceptors freeze. This further reduces the proportion of holes flowing via the sidewall of V-pits in sample B. As the temperature decreases, the increase of the voltage of sample B is higher than that of sample A.

Fig. 5 shows the EL spectra of the two experimental samples at various injection currents at 100 K. P1 and P2 are emitted from the QWs closer to p-GaN and the QWs closer to n-GaN, respectively. P3 is emitted from the sidewalls QWs. It is worth noting that P3 in sample B emerges at a lower current

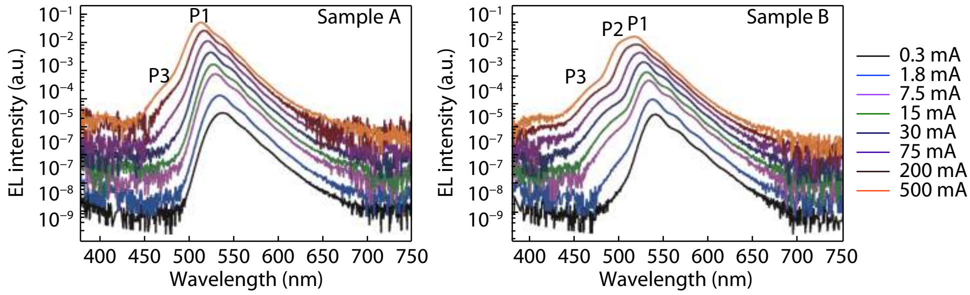

Fig. 5. (Color online) The EL spectra of two experimental samples at various injection currents at 100 K.

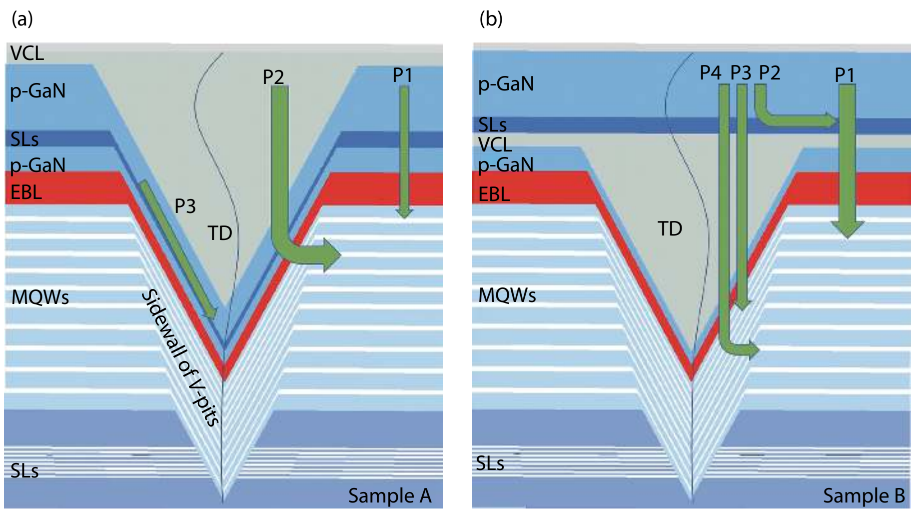

Fig. 6. (Color online) Schematic diagram of the potential transport paths of holes in two samples with different position of VCL.

density and is more manifested than that in sample A. This indicates that the holes in sample B injected into the sidewall QWs take part in radiative recombination with electrons more easily than that in sample A. The observed emission of P2 from the deeper QWs near the n-GaN in sample B demonstrates that the holes in sample B could be transported further than those in sample A. Based on the correlation analysis of structural characteristics and the *I*–*V* characteristics of two samples mentioned above, these phenomena should be correlated with the increased kinetic energy of holes, which changes the transport paths of holes in sample B. For a better understanding of the changes in the transport paths, Fig. 6 schematically display the possible transport paths of holes in two samples with different VCL positions. At room temperature, most of the holes in sample B were normally injected into MQWs via path 1 and path 2 due to the high resistance in the V-pits. However, when the temperature decreases, the higher operating voltage of sample B can speed up the holes. This gives the holes enough kinetic energy to inject into the sidewall of V-pits via path 3. Hence, when most of the holes injected into sidewall QWs of V-pits in sample A are diffused into the *c*-plane QWs via the path 2 provided by V-pits[9], the holes injected into the sidewall QWs of V-pits in sample B could be transported further via path 3 due to the higher kinetic energy. This means that the holes have more opportunity to participate in radiative recombination with electrons in the sidewall QWs. Then, when the five QWs near the p-type layer are filled up with the injection current increase, the holes can transport to deeper QWs near the n-type layer via path 4. This leads to the manifested emission of P2 in sample B, which also accounts for the lower EQE of sample B at region II at cryogenic temperatures. In addition, the suppressed Shockley–Read–Hall recombination that resulted from the decrease of temperature might also contribute to these phenomena[21].

4. Conclusion

In summary, the effect of VCL position on the optoelectronic performance of high-efficiency green LEDs has been studied. It was found that the earlier covering of V-pits will hinder the hole injection via the sidewall of V-pits, and then result in a higher EQE at low current density and an earlier droop with the increasing current density. Meanwhile, the reduced proportion of hole injection via the sidewall of V-pits also results in a higher operating voltage at room temperature and a dramatic increase in voltage as the temperature decreases. The higher operating voltage gives the hole injected via the sidewall of V-pits higher kinetic energy. This then leads to the emissions of sidewall QWs and deeper QWs near to n-type layer. Finally, the results of this investigation show that the VCL should be properly doped to provide suitable hole concentration and operating voltage.

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