Study of efficiency droop in InGaN/GaN light emitting diodes with V-shape pits

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ABSTRACT

We invesstagated the relationship between the emission efficiency of InGaN/GaN multiple quantum wells (MQWs) and the V-shape pits (V-pits) forming along the threading dislocation (TD). The thinner InGaN/GaN MQWs on the side walls around V-pits would create higher local energy barriers, which can resist the carriers trapped into the non-radiative recombination centres within TDs. By inserting different InGaN/GaN superlattice (SLS) layers below the MQWs, sizes of V-pits could be properly controlled. It was found that the V-pit size on InGaN MQWs increased with increasing SLS layers, which could decrease energy barriers. On the contrary, the shorter distance between the TD center and V-pit boundary would increase the carrier capturing capability of TDs in smaller V-pits. By properly controlling the V-shape defect formation, the best internal quantum efficiency of about 70%f was found in the MQWs with underlying 15 periods SLS layers.

Keywords: V-pit defect, internal quantum efficiency (IQE), droop efficency

1. Introduction

InGaN/GaN light emitting diodes (LEDs) are now widespread used in solid-state lighting, because of their high luminescence efficiency and potential to replace traditional lighting sources [1]. However, there are plenty threading dislocations (TD) occurred during the epitaxial process due to lattice mismatch between the GaN and sapphire substrate [2]. The high threading dislocations density will lead to the enhancement of non-radiative recombination centers and current leakage paths [3]. Despite pattern sapphire substrates (PSS) are applied to reduce the TD density, dislocation

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density as high as around 10^8 cm^{-2} is typically observed. The previous reports showed that TDs could form V-shape pits (V-pits) on InGaN multiple quantum wells (MQWs). It has the narrower MQW on the inclined V-pit planes, forming energy barriers to effectively block carriers into TDs to retain the emission efficiency [4]. Therefore, it's inevitable to study the effect of defects on the blue LED efficiency. Meanwhile, the formation of V-pits also help to increase the light extraction efficiency because of the inverted hexagonal inclined planes [5-7]. In addition, the p-type GaN right on top of V-pits has been claimed to show lower Mg incorporation and the localized high resistance could effectively block the current leakage to TDs [8-9] . Furthermore, the formation of V-pits in MQW could facilitate hole injection into deeper QWs to uniformly distribute hole carriers in active layers to improve the efficiency droop [10]. In this study, the relationship between the light emission efficiency of InGaN/GaN MQWs and V-pits formation was systematically analysed. In order to clarify the effects of V-shape pits, we inserted different periods of InGaN/GaN superlattice (SLS) layers ranging from 0, 10, 15, 30 and 60 below the MQWs to control the properties of V-shape pits.

2. Experimental procedures

The epitaxial structures including 3.5 μm un-doped GaN (u-GaN) and 2 μm n-doped GaN (n-GaN) layers were grown on the c-plane pattern sapphire substrate (PSS) by metal-organic chemical vapor deposition. Then, four types of samples of InGaN/GaN SLS layers with different periods ranging from 0, 10, 15, 30 and 60 were grown on the n-GaN layer. The thickness of one superlattice period was about 6 nm. Fig. 1(a) and (b) show the top-viwe scanning electron microscopy (SEM) image of 10 and 60 pairs InGaN SLS samples. It can be clearly observed the presence of V-pits on the surface of SLS layer and the V-pit size increased with increasing the pairs of SLS. In the following, the InGaN/GaN MQWs were grown and comprised with first 6 pairs of shallower MQWs with In composition of about 10% and then 9 pairs of deeper MQWs with In composition of about 20 %. The thickness of InGaN well and GaN barrier were 2.8 nm and 13 nm, respectively. Again, the V-shape pits were observed for all samples by using the optical microscopy (OM) of BX50 Olympus Microscope and SEM. Then, the optical properties of InGaN MQWs with varing V-pit size were characterized by using photoluminescence (PL), and cathodoluminescence (CL) measurement.

3. Results and discussion

Fig. 1(c) shows the OM image of PSS rendering a hexagonal lattice pattern. The diameter of a circle basis was about 3 μm and the lattice constant was about 4 μm. The spatial frequency of the PSS could be calculated by Fourier transform. The reciprocal space of Fig. 1(d) clearly shows a 30-degree rotated hexagonal lattice compared with Fig. 1(c). The V-pit distribution on MQWs with 15 pairs SLS was investigated by SEM measurement as shown in Fig. 1(e). The V-pit density was approximately 1.6×10^8 cm^2 and a similar order of V-pit density was observed in all other samples. Although the V-pits looked pretty randomly distributed, the reciprocal space of those V-pits still exhibited a rotated-back hexagonal lattice as shown in Fig. 1(f). High correlation between the distribution of PSS and the formation of V-pits could be drawn due to the fact that the threading edge dislocation would dominate the formation of V-pit. This kind of TD would extend along the c direction originating from the flat c-plane region of PSS and triggered the V-pit formation from the termination of threading edge dislocation [11]. Consequently, V-pits distribution naturally related to the pattern of PSS.

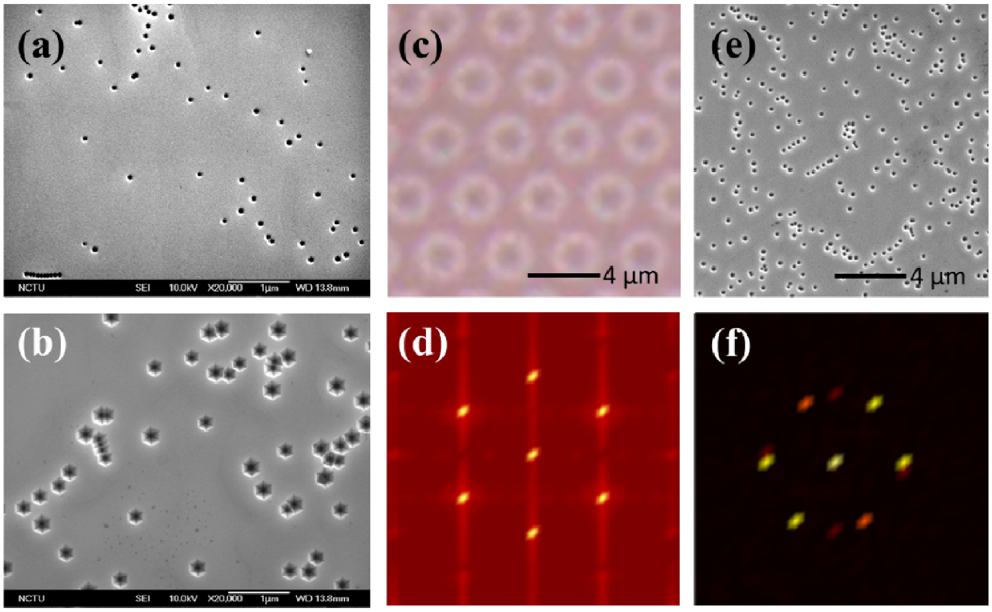

Fig. 1(a) the top-view of SEM–image of 10 pairs InGaN/GaN SLS with formation of V-pit grown on PSS. (b) the top view of SEM–image of 60 pairs InGaN/GaN SLS with formation of V-pit grown on PSS. (c) OM-image for the pattern of PSS. (d) Reciprocal space distribution of PSS by applying the Fourier transform of OM-image in (c). (e) Top view of SEM–image of MQWs with V-pits. (f) Reciprocal space distribution for the morphology of MQW with V-pits by applying the Fourier transform of SEM-image in (e).

Figs. 2 (a)-(d) show the top view of SEM–image for InGaN/GaN MQWs with formation of V-pits grown on the template of 10, 15, 30 and 60 pairs SLS. The V-pit size on MQWs increased with increasing the numbers of SLS layers. The diameters of V-pit size on MQWs with 10, 15 30 and 60 pairs SLS were 130- 250 nm, 150-270 nm, 220-350 nm and 330-470 nm, respectively. The monochromatic CL-images of MQWs with 10, 15, 30 and 60 pairs SLS at 450 nm are shown in Fig. 2 (e)-(g). The dark spots basically relected the positions of V-pits shown in Figs. 8(a)-(d), which represented the non-radiative recombination centers. However, for the regions without V-pits, the sample of InGaN MQWs with 10 pairs SLS showed weaker emission intensity than those with 15 and 30 pairs SLS. This could be due to the fact that the V-pit size could be so small on the sample with 10 pairs SLS that carriers could be easier trapped by the TD to reduce the emission intensity. On the contrary, the V-pit size were too large on the InGaN MQWs with 60 pairs InGaN SLS so that the emssion area of InGaN MQWs was greatly reduced.

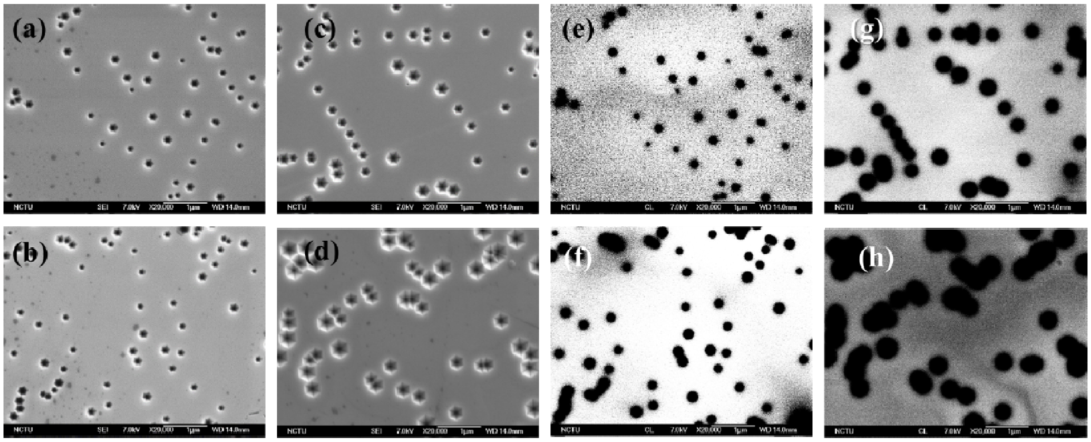

Fig. 2 (a) The SEM–image of V-pit for InGaN MQW with 10 pairs InGaN SLS. (b) The SEM–image of V-pit for InGaN MQW with 15 pairs InGaN SLS. (c) The SEM–image of V-pit for InGaN MQW with 30 pairs InGaN SLS. (d) The SEM–image of V-pit for InGaN MQW with 60 pairs InGaN SLS. (e) The plane-view monochromatic CL image at 450 nm of InGaN MQW with 10 pairs InGaN SLS. (f) The plane-view monochromatic CL image at 450 nm of InGaN MQW with 15 pairs InGaN SLS. (g) The plane-view monochromatic CL image at 450 nm of InGaN MQW with 30 pairs InGaN SLS. (h) The plane-view monochromatic CL image at 450 nm of InGaN MQW with 60 pairs InGaN SLS.

Fig. 3(a) shows the low temperture PL spectra versus the excitation power at 10K of InGaN MQWs with 30 pairs SLS. The emission peak of shallow InGaN/GaN MQWs and deeper InGaN/GaN MQWs were at 417 nm and 450 nm. The shoulder emission peak at 432 nm was clearly observed with increasing the excitation power. This peak could be attributed to the emission of sidewall InGaN/GaN MQWs on V-shape pit duo to the thinner sidewall quantum wells to create higher emission energy in the semi-polar face. Fig. 3(b) shows the emission peak energy of sidewall InGaN MQW as a function of SLS layers at the excitation power of 20 mW and the IQE value of InGaN/GaN MQW with varying InGaN SLS layers. The peak energy of sidewall InGaN MQW reduced with increasing the numbers of InGaN SLS layers. Since the V-pit size on InGaN MQWs increased with increasing pairs of SLS, thicker sidewall quantum wells were expected and lower local energy barriers were then formed around V-shape pits, which could reduce the IQE values. However, the V-pit size for the InGaN MQWs with 10 pairs SLS could be so small that carriers could be easier trapped by the TD to reduce the emission intensity. Therefore, the best IQE value of about 70% was obtained in the InGaN MQWs with 15 pairs SLS. In addition, the normalized PL emission efficiency of InGaN MQWs with 10 and 60 pairs was shown in Fig. 2(c) and (d). It can be found that the PL emission efficiency droop of InGaN MQWs started at the onset of the emission from the sidewall MQWs on V-pits. At a high excitation power, those high energy carriers could have more chances to flow over those energy barriers around the V-pits, leading to the occurrence of serious droop phenomenon of InGaN MQWs. As a result, a proper V-pit structure could be engineered to improve the droop behaviours.

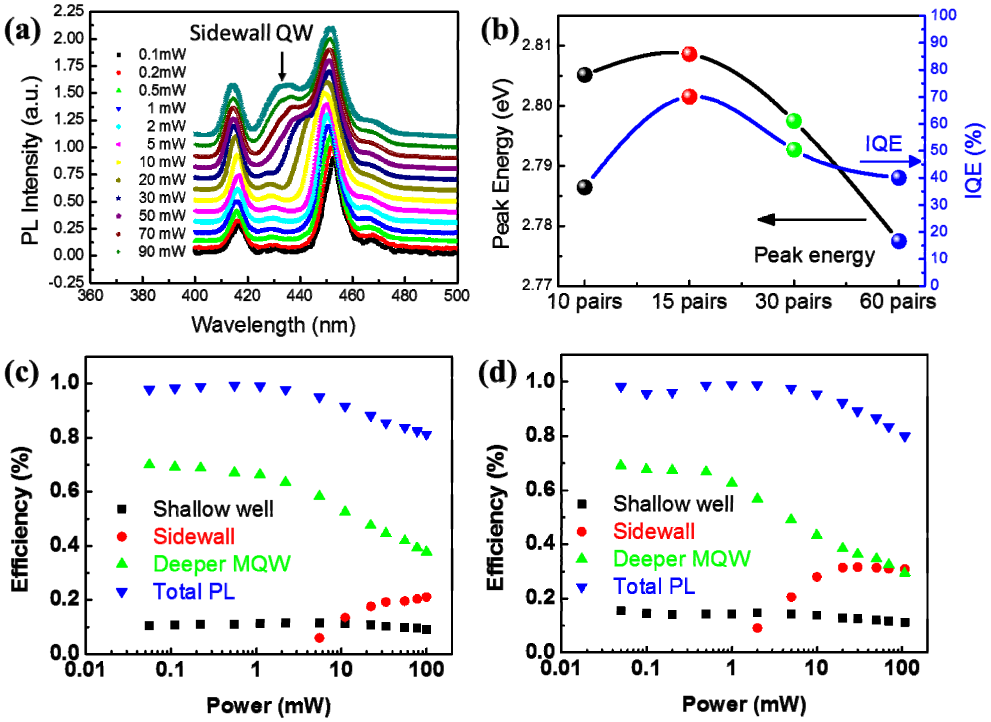

Fig. 3 (a) The power dependent PL spectra for the InGaN/GaN MQW with 30 pairs SLS at 10K. (b) The emission peak energy of sidewall InGaN MQW as a function of SLS pairs at the temperature of 10K and the IQE value of InGaN/GaN MQW with varying InGaN SLS layers. (c) The emission efficiency of intgrated PL spectra for shallow, deeper and sidewall of InGaN MQWs with 10 pairs SLS as a function of excitation power at the temperature of 10K. (d) The emission efficiency of intgrated PL spectra for shallow, deeper and sidewall of InGaN MQW with 60 pairs SLS as a function of excitation power at the temperature of 10K.

4. Conclusion

The relationship between the emission efficiency of InGaN/GaN MQWs and the different V-shape pits was investigated. The thinner sidewall MQWs around V-pits could serve as local energy barriers to block the carriers trapped into the non-radiative recombination centres within the V-pits originating from TDs. The V-pit size on InGaN MQWs increased with increasing SLS layers, which would widen the QW thickness and decrease the barrier energy. On the contrary, the shorter distance between the TD center and V-pit boundary in smaller V-pits would increase the carriers capturing capability of TDs. Therefore, an optimized V-pit size could be benificial to preserve the emission efficiency in InGaN MQWs and improve the droop behavior. In our experiments, the best IQE value of 70% was obtained in InGaN MQWs with 15 pairs SLS. We believe that further optimiztion of V-pit structures by using various growth conditions can shed light on making high performance InGaN LEDs in the near future.

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Reference

[1] Dupuis, R. D. and Krames, M. R., "History, Development, and Aplications of High-Brightness Visible Light-Emitting Diodes, " IEEE J. Lightwave Technol., 26 (9),1154-1171 (2008).

[2] LeGoues, F. K., "Self-aligned sources for dislocation nucleation: The key to low threading dislocation densities in compositionally graded thin films grown at low temperature, " Phys. Rev. Lett.**,** 72 (6), 876-879 (1994).

[3] Schubert, M. F., Chhajed, S., Kim, J. K., Schubert, E. F., Koleske, D. D., " Crawford, M. H.; Lee, S. R.; Fischer, A. J.; Thaler, G.; Banas, M. A., Effect of dislocation density on efficiency droop in GaInN/GaN light-emitting diodes, " Appl. Phys. Lett.**,** 91 (23) (2007).

[4] Hangleiter, A.; Hitzel, F.; Netzel, C.; Fuhrmann, D.; Rossow, U.; Ade, G.; Hinze, P., " Suppression of nonradiative recombination by V-shaped pits in GaInN/GaN quantum wells produces a large increase in the light emission efficiency, " Phys. Rev. Lett.**,** 95 (12), 127402 (2005).

[5] Yong, A.; Soh, C.; Zhang, X.; Chow, S.; Chua, S., " Investigation of V-defects formation in InGaN/GaN multiple quantum well grown on sapphire, " Thin Solid Films**,** 515 (10), 4496-4500 (2007).

[6] Tsai, H.; Wang, T.; Yang, J.; Chuo, C.; Hsu, J.; Feng, Z.; Shiojiri, M., " Observation of V defects in multiple InGaN/GaN quantum well layers, " Mater. Trans.**,** 48 (5), 894 (2007).

[7] Shiojiri, M.; Chuo, C.; Hsu, J.; Yang, J.; Saijo, H., " Structure and formation mechanism of V defects in multiple InGaN/GaN quantum well layers, " J. Appl. Phys.**,** 99 (7), 073505 (2006).

[8] Han, S.H.; Lee, D.Y.; Shim, H.W.; Lee, J. W.; Kim, D.J.; Yoon, S.; Kim, Y. S.; Kim, S.T., " Improvement of efficiency and electrical properties using intentionally formed V-shaped pits in InGaN/GaN multiple quantum well light-emitting diodes, " Appl. Phys. Lett.**,** 102 (25), 251123 (2013)

[9] Kim, J.; Cho, Y.H.; Ko, D.S.; Li, X.S.; Won, J.Y.; Lee, E.; Park, S.H.; Kim, J.Y.; Kim, S., " Influence of V-pits on the efficiency droop in InGaN/GaN quantum wells, " Opt. Express**,** 22 (103), A857-A866 (2014).

[10] Sharma, N.; Thomas, P.; Tricker, D.; Humphreys, C., " Chemical mapping and formation of V-defects in InGaN multiple quantum wells, " Appl. Phys. Lett.**,** 77 (9), 1274-1276 (2000).