Influence of growth conditions on the V-defects in InGaN/GaN MQWs*

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Abstract: The influence of the growth temperature, TMIn/TEGa and V/III ratio on the V-defects of InGaN/GaN multi-quantum wells (MQWs) has been investigated and discussed. When the TMIn flow increases from 180 to 200 sccm, the density of V-defects increases from 2.72×10^{18} to 5.24×10^{18} cm^{-2}, and the V-defect width and depth increase too. The density also increases with the growth temperature. The densities are 2.05×10^{8}, 2.72×10^{18} and 4.23×10^{8} cm^{-2}, corresponding to a growth temperature of 748, 753 and 758 ℃ respectively. When the NH_3 flows are 5000, 6600 and 8000 sccm, the densities of the V-defects of these samples are 6.34×10^{18}, 2.72×10^{18} and 4.13×10^{18} cm^{-2}, respectively. A proper V/III ratio is needed to achieve step flow growth mode. We get the best quality of InGaN/GaN MQWs at a growth temperature of 753 ℃ TMIn flow at 180 sccm, NH_3 flow at 6600 sccm, a flatter surface and less V-defects density. The depths of these V-defects are from 10 to 30 nm, and the widths are from 100 to 200 nm. In order to suppress the influence of V-defects on reverse current and electro-static discharge of LEDs, it is essential to grow thicker p-GaN to fill the V-defects.

Key words: V-defect density; width; depth; TMIn/TEGa; NH_3; temperature

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1. Introduction

InGaN or InGaN/GaN multiquantum wells (MQWs) are widely used as the active layer of light emitting diodes (LED) covering from near ultraviolet to green. InGaN alloys tend to undergo both phase separation and long-range atomic ordering, which give rise to potential energy fluctuations due to compositional inhomogeneities[1]. V-defects formed in InGaN or InGaN/GaN have great influence on the InGaN/GaN LED breakdown voltage, reverse current (I_R) and electro-static discharge (ESD)[2−5]. To improve the performance of LEDs, it is important to study the influence of growth conditions on the V-defects of InGaN/GaN MQWs.

Indium segregation in the vicinity of the V-defects is suggested to be responsible for V-defect formation and has a strong influence on the optical properties. The structure of the V-defects includes buried side-wall quantum wells (on the $\langle 10\bar{1}1\rangle$ planes) and an open hexagonal inverted pyramid[6]. Each V-defect has at its center a threading edge dislocation, indicating that the defects are initiated at edge dislocation cores in the presence of indium[2].

2. Experiment

A series of InGaN/GaN multi-quantum well structures were grown in different conditions. The InGaN/GaN MQW samples used in this study were grown on a c-plane (0001) sapphire substrate with a VEECO metal-organic chemical vapor deposition (MOCVD) system using a high speed rotating disk with a vertical gas-flow growth chamber. Trimethylgallium (TMGa), trimethylindium (TMIn), triethylgallium (TEGa), and ammonia (NH_3) were used as precursors of Ga, In, and N, respectively. H_2 and N_2 were used as the carrier gas.

First, the sapphire was annealed at 1100 ℃ in H_2 atmosphere, then cooling down the reactor and nitrided by NH_3 at 550 ℃. A 20 nm thick GaN nucleation layer was deposited at 550 ℃. The temperature was then raised to 1050 ℃ to grow a 2 μm thick undoped-GaN layer. All of the 8× InGaN/GaN MQWs were grown on these GaN templates. A low temperature GaN cap layer was grown on each InGaN well to protect InGaN from decomposition. The first 4 quantum barriers were slightly silicon doping. These MQWs were all grown at 400 mbar. N_2 was used as the carrier gas for these MQWs. The growth conditions of these MQWs are listed in Table 1.

To investigate the influence of growth conditions on V-defects in InGaN/GaN MQWs, six samples are grown. After growth, high-resolution X-ray diffraction (HRXRD) is performed to characterize the structural quality and strain state of the samples by the Bede D1 system, as shown in Fig. 1. We can clearly see the fourth satellite peaks of all of the samples. The quality of these InGaN/GaN MQWs was comparable and all have an abrupt interface. As-grown wafers were characterized

Table 1. Growth conditions of InGaN/GaN MQWs.

Sample no.	Press (mbar)	Temp (℃)	NH_3 (sccm)	TEGa (sccm)	TMIn (sccm)
A	400	753	6600	20	200
B	400	753	5000	20	180
C	400	748	6600	20	180
D	400	753	6600	20	180
E	400	758	6600	20	180
F	400	753	8000	20	180

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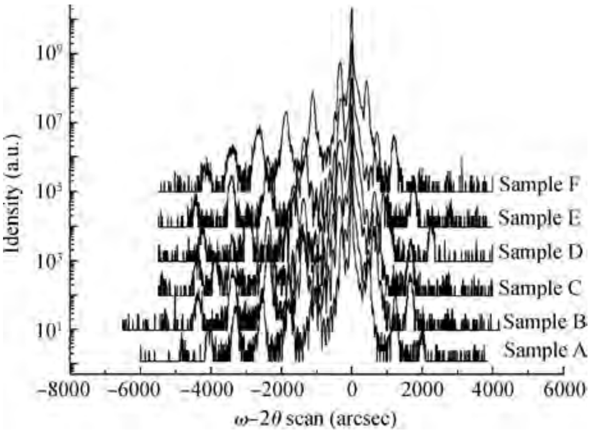

Fig. 1. XRD ω–2θ scan of InGaN/GaN MQWs grown in different conditions.

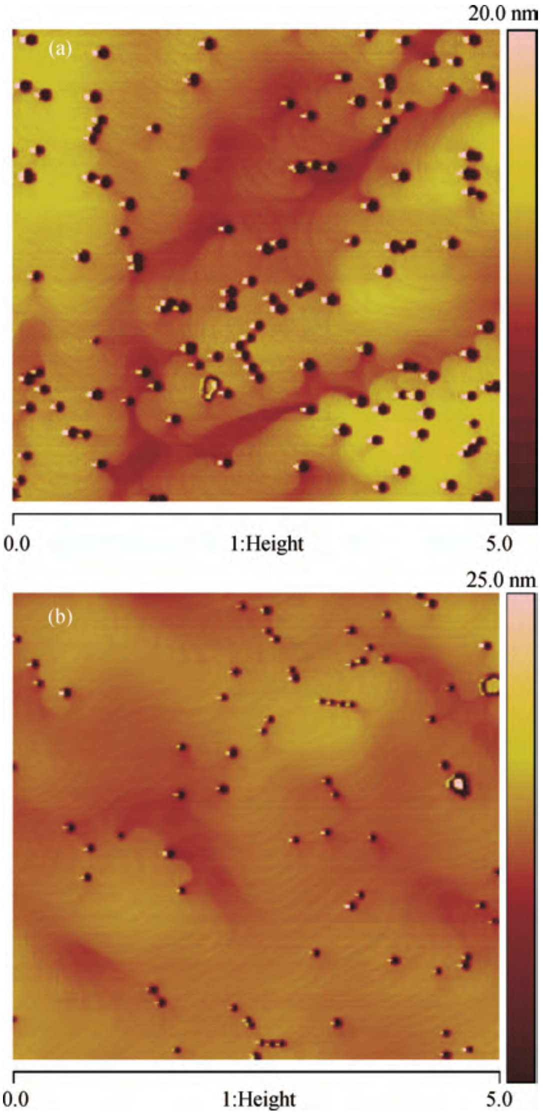

Fig. 2. AFM images of InGaN/GaN MQWs grown at different TMIn/TEGa ratios. (a) Sample A. (b) Sample D.

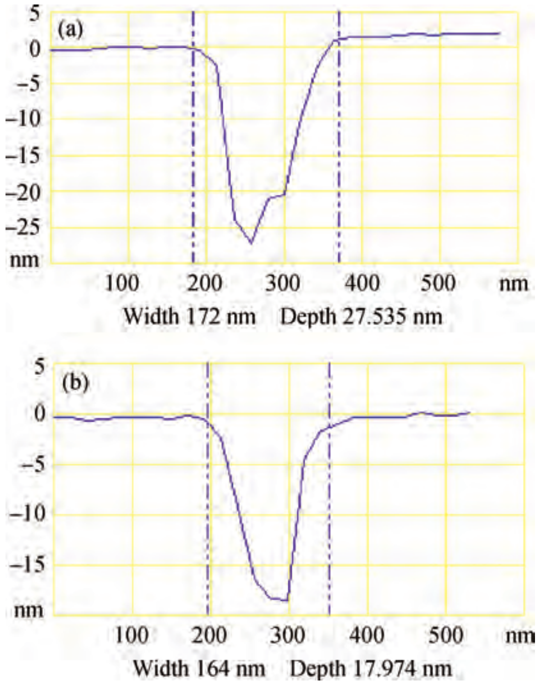

Fig. 3. Cross-section analysis of the V-defects of (a) samples A and (b) D.

by measuring their photoluminescence (PL). The samples were optically pumped with a 30 mW He–Cd laser emitting at 325 nm. Surface morphology is characterized using atomic force microscopy (AFM). We scan 9 points for each sample, and the scanned area is 5 μm × 5 μm. The density of V-defects is the average number of these 9 points. In addition, we take 10 V-defects from each sample to get the average depth and width.

3. Results and discussion

3.1. Influence of TMIn/TEGa

For samples A and D, to avoid the influence of growth rate, we keep the TEGa flow at 20 sccm, and change the TMIn flow from 200 to 180 sccm to get different TMIn/TEGa ratios. The density of V-defects decreases with the TMIn flow. The density of V-defects decreases from 5.24×10^{18} to 2.72×10^{18} cm^{-2}, as shown in Fig. 2, indicating that the TMIn flow has great influence on the density of V-defects. A higher TMIn/(TMIn + TEGa) ratio will increase mismatch dislocations in InGaN/GaN MQWs and induce more V-defects[7]. However, the change in indium mole fraction in InGaN is very small compared with that of the change in TMIn flow, because the TMIn is difficult to merge into the InGaN at the growth temperature of 753 ℃. Therefore a proper TMIn/TEGa ratio is needed for high quality InGaN/GaN MQWs. Meanwhile, the width and depth of V-defects both increase with increasing TMIn flow, as shown in Fig. 3. The depth of these V-defects is in the range of 10 to 30 nm, and the width is from 100 to 200 nm, which are comparable to the data from previous reports[8].

3.2. Influence of temperature

For samples C, D and E, keeping the other conditions the same, the temperatures are 748, 753 and 758 ℃ respectively, and the corresponding V-defect densities are 2.05×10^8, 2.72×10^8 and 4.23×10^8 cm^{-2}, which are shown in Fig. 4. We can clearly see that the density of V-defects increases with increas-

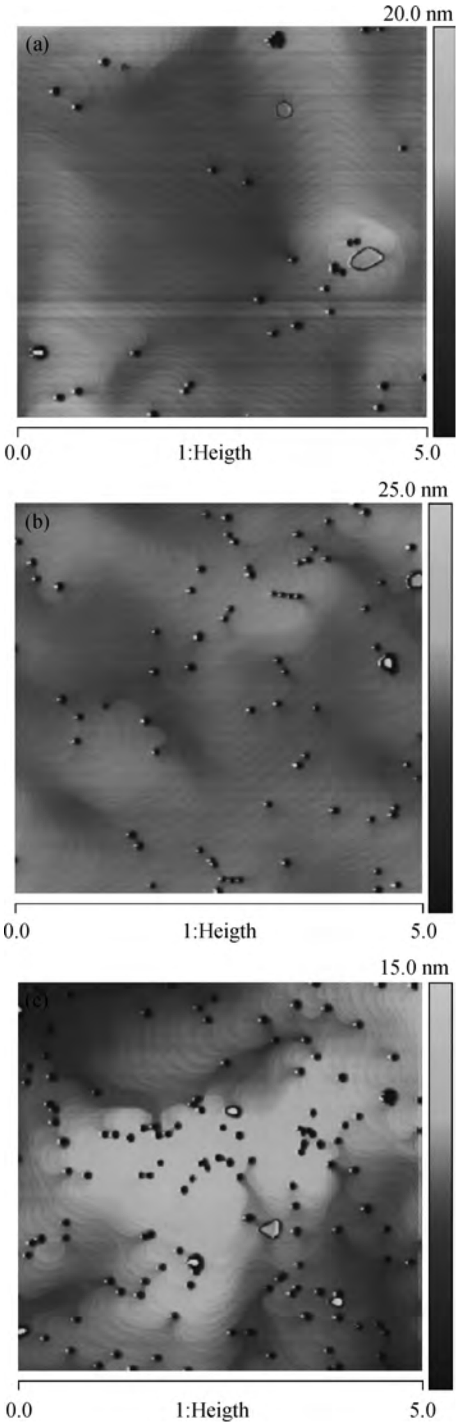

Fig. 4. AFM images of InGaN/GaN MQWs grown at different temperatures. (a) Sample C. (b) Sample D. (c) Sample E.

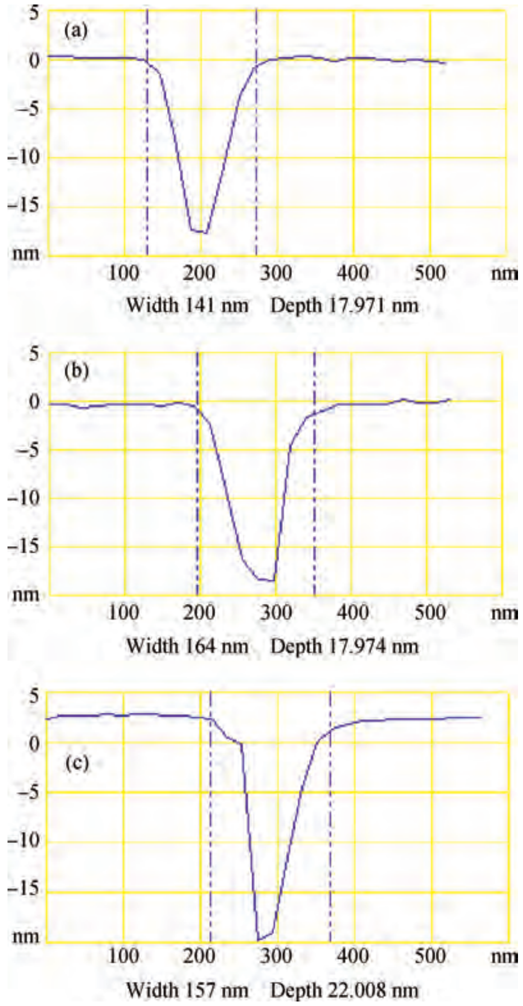

Fig. 5. Cross-section analysis of the V-defects of samples (a) C, (b) D and (c) E.

ing growth temperature. This is because at higher growth temperatures, the segregation of indium severely leads to more V-defects and a rougher surface. Decrease the growth temperature of InGaN/GaN MQWs, though the crystal quality will deteriorate, the indium segregation will be weaker. Lee *et al.*[9] also found that the In composition in InGaN increases as the growth temperature decreases, and the V-defect density increases with the growth temperature. The indium mole fraction of InGaN decreases with the growth temperature, which we can get from the PL test peak wavelengths of these samples. With increasing growth temperature, the widths of V-defects don't change much, but the depths of V-defects increase with the temperature, as shown in Fig. 5.

3.3. Influence of V/III

For samples B, D and F, in order to avoid the influence of TEGa and TMIn flow, we keep the TMIn and TEGa flow the same, and change the NH_3 flow to get different V/III ratios. The NH_3 flows are 5000, 6600, and 8000 sccm, respectively, and the densities of V-defects are 6.34×10^{18}, 2.72×10^{18}, and 4.13×10^{18} cm^{-2}, as shown in Fig. 6. When the NH_3 flow increases from 5000 to 6600 sccm, the V-defect density decreases from 6.34×10^{18} to 2.72×10^{18} cm^{-2} , but the width and depth of V-defects increase, as shown in Fig. 7. When the NH_3 flow increases from 6600 to 8000 sccm, the V-defects increase from 2.72×10^{18} to 4.13×10^{18} cm^{-2}, but the width and depth of the V-defects doesn't change much. The surface of samples B and F is rougher than that of sample D. This is because when the NH_3 flow is low, InGaN is in spiral hill growth mode, increasing the NH_3 flow, and will change spiral hill mode to step flow mode. More NH_3 is beneficial for indium merging into InGaN films, but a large flow of NH_3 will change the growth mode of InGaN films from step flow to Stranski-Krastanov

Table 2. Average V-defect width, depth, density of InGaN/GaN MQWs.

Sample No.	PL wavelength (nm)	Average V-defect width (nm)	Average V-defect depth (nm)	Average V-defect density (10^8 cm^{-2})
A	490.708	172	27.535	5.24
B	453.319	133	14.481	6.34
C	484.350	141	17.971	2.05
D	480.619	164	17.974	2.72
E	461.034	157	22.008	4.27
F	503.341	157	16.728	4.13

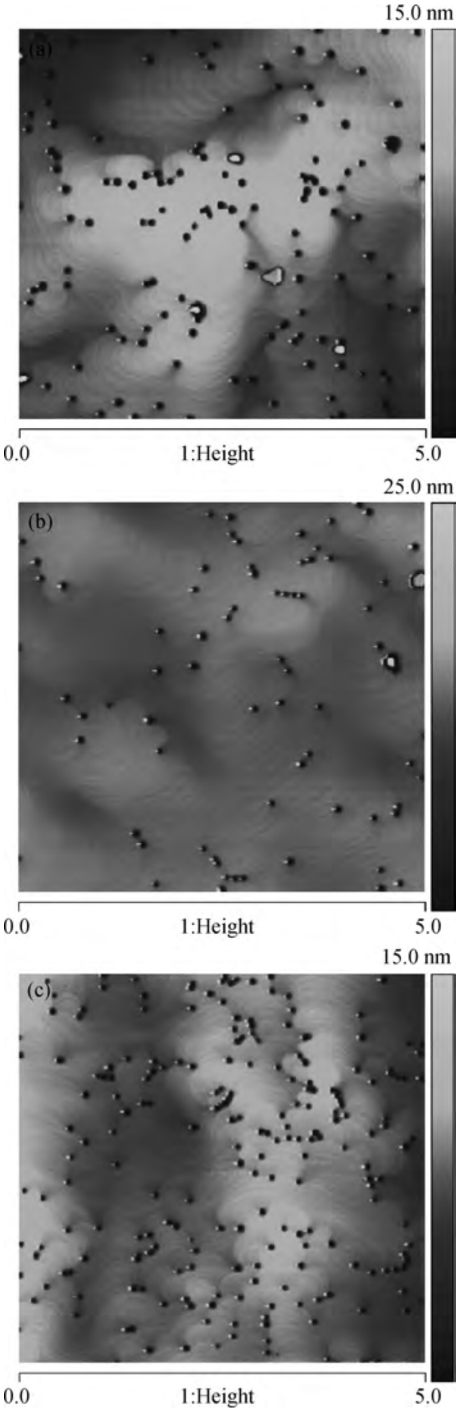

Fig. 6. AFM images of InGaN/GaN MQWs grown at different V/III. (a) Sample B. (b) Sample D. (c) Sample F.

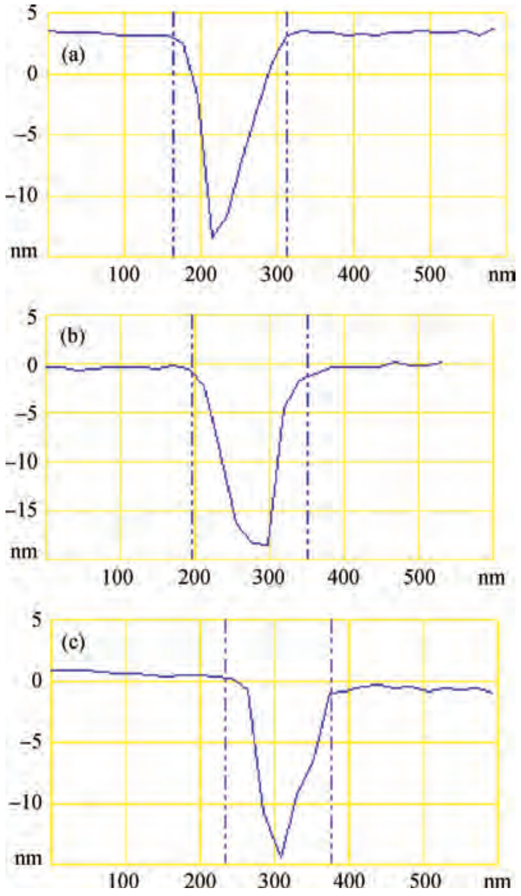

Fig. 7. Cross-section analysis of the V-defects of samples (a) B, (b) D and (c) F.

mode, causingV-defects and surface roughness[10], and the InGaN films deteriorate[11]. Increasing the NH_3 flow, the indium mole fraction increased in InGaN films, which is shown in Table 2. NH_3 is not easy to crack at the InGaN growth temperature of 753 ℃, and increasing the NH_3 flow will provide more N for InGaN films.

4. Conclusion

The V-defects in these InGaN/GaN MQWs are formed when threading dislocations intersect the epi-layer surface. The formation of V-defects in InGaN/GaN MQWs mainly depends on the indium composition fluctuation[12, 13]. When the TMIn flow increases from 180 to 200 sccm, the density of V-defects increases from 2.72×10^{18} to 5.24×10^{18} cm^{-2}, and the width and depth also increase. With the temperature increase from

748 to 758 ℃, the densities are 2.05×10^8, 2.72×10^8 and 4.23×10^8 cm^{-2}, respectively. The V-defect density increases with increasing growth temperature. When the NH_3 flow changes from 5000 to 8000 sccm, the densities are 6.34×10^{18}, 2.72×10^{18} and 4.13×10^{18} cm^{-2}, and the NH_3 flow has great influence on the growth mode of InGaN films. A proper V/III ratio is needed to achieve step flow growth mode. Lower TMIn/TEGa ratio, proper NH_3 flow and lower growth temperature will decrease the V-defect density. On the other hand, higher V/III is essential for InGaN growth, and lower growth temperature will degrade the crystal quality of InGaN films. So it is important to choose the proper V/III ratio, TMIn/TEGa ratio and temperature for InGaN/GaN growth. We get the best quality of InGaN/GaN MQWs at a growth temperature of 753 ℃, TMIn flow at 180 sccm, NH_3 flow at 6600 sccm, with a flatter surface and a lower V-defect density. The depths of these V-defects are from 10 to 30 nm and the widths are from 100 to 200 nm. In order to suppress the influence of V-defects on reverse current and the ESD of LEDs, it is essential to grow thicker p-GaN to fill the V-defects[14].

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