Effects of InGaN-interlayer on closed stripes of GaN grown by serpentine channel patterned sapphire substrate

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Abstract

Gallium nitride (GaN) is a widely investigated semiconductor owing to its fascinating features suitable for a plethora of optoelectronic applications; nevertheless, high-quality growth of this material remains a challenge. In this work, the crystal quality of GaN grown by serpentine channel patterned sapphire substrates (SCPSS) is improved via introducing indium gallium nitride (InGaN) as an interlayer (IL). The closed stripes of GaN are grown by the modified design of SCPSS. Our results show that the crystal quality of GaN grown in the form of closed stripes is superior than conventionally grown counterpart. Transmission electron microscopy (TEM) revealed that the design of SCPSS controls all threading dislocations (TDs) while cathodoluminescence (CL) analysis showed that the closed stripes are relaxed and produce many TDs. Therefore, further control over the TDs was achieved by InGaN-IL. During the growth process, the temperature of GaN was reduced and 20 nm thick InGaN-IL was added at 800 °C. The detailed characterization of our developed samples indicated that the additional use of InGaN-IL in SCPSS is very effective for improving the crystal quality of GaN. We anticipate that our findings will improve the current understanding about the growth of high-quality GaN towards efficient optoelectronic devices.

1. Introduction

Gallium Nitride (GaN) is a III/V compound semiconductor that is commonly used to fabricate green-to-ultraviolet light-emitting diodes (LEDs), laser diodes (LDs) as well as high-power and high-speed optoelectronic devices [1–6]. Despite all these benefits, the further applications of GaN-based devices are hindered due to the lack of native substrates. The growth of these devices on heterogeneous substrates, such as sapphire, SiC, and Si is a technical challenge [7] as large lattice and thermal mismatch between GaN and such conventional substrates produce huge numbers of threading dislocations (TDs) [8].

According to Zhu et al the lattice-mismatched epilayers have a high density of TDs and reduce the electrical reliability of GaN-based devices. When defects occur in the materials, the defect energy level might be introduced into the energy band and give different optical signals [9]. According to Dash et al and Khan et al TDs, provides leakage current conduction path. These TDs are one or more open-core TDs, pure-screw TDs, edge-type TDs, and mixed-type TDs. Screw TDs and open TDs originating from polygonal pits are responsible for excess leakage current. They are also acting as nonradiative recombination centers and charge scattering sites. Besides these TDs, the existence of native defects also impacts the optoelectronic properties [10, 11].

High-quality GaN has been developed via epitaxial lateral overgrowth (ELO) and its derivatives such as pendeo-epitaxy (PE) [12] and cantilever epitaxy (CE) [13, 14]; however, these multi-step processing techniques lead to very high production costs [15–17]. Alternatively, the crystal quality of GaN was improved by employing a sapphire substrate masked with the serpentine channel. The internal quantum efficiency (IQE) of multi-
quantum wells (MQWs) grown by serpentine channel patterned sapphire substrates (SCPSS) was 52% higher than that of conventionally developed counterparts [8]. Additionally, such single-step growth consumes lower energy and is conveniently transferable to another substrate [7]. It was observed that in the case of coalescence growth, the growth fronts meet at mid of two adjacent windows and produce defective areas called meeting-fronts [18]. To further improve the quality of GaN, these defective areas were removed by selective area growth (SAG) of GaN. The patterned growth of GaN was introduced in the form of closed stripes and growth was terminated before the occurrence of meeting-fronts. In this way, the most defective areas were removed from meeting-fronts. In addition, the SAG of GaN has attracted much attention as a technique to improve the crystal quality or to fabrication the microstructures of electrical and optical devices with high performance. Therefore, the growth of GaN was introduced in the form of closed stripes. However, in SAG, the strain relaxation is appeared due to the long growth time which affects the crystal quality of GaN. CL shows that closed stripes are relaxed and generate many TDs. Despite using PSS, we could not control all TDs. The long growth time of GaN induces stress building in the GaN and after stress relaxation, many TDs are gliding in the m-plane [19]. Despite using PSS, the generation of many TDs is surprising therefore, the strain relaxation and gliding of TDs were controlled by InGaN-IL. Okada et al [19] also investigated that the SAG of GaN grown in the form of bar-shaped growth. The long growth time in SAG produces dark spots along a line which are described as line defects. Further increasing the thickness of the GaN layer generate large numbers of lines defects in a specific direction. It was assumed that defects appear through a glide of the m-plane, which corresponds to the interpretation for Peierls stress of the m-plane. These line defects do not emit any wavelength which are inclined to c-plane and glide in the m-plane of the GaN. To deal with this issue, the addition of IL is very useful. Recently, many researchers improved the crystal quality of GaN by the addition of ILs of different materials including Aluminum nitride (AlN) [20], Scandium Nitride (ScN) [21], and InGaN [22]. The ILs of these materials drastically reduced the clusters of TDs. Therefore, to further improve the crystal quality of GaN, the growth of GaN, growth temperature of GaN was ramped down and 20 nm thick InGaN-IL was added at 800 °C. Although, the use of interlayer for reduction of TDs is an old technique, however, the further reduction of TDs by interlayers in pattern growth is rarely discussed. CL, Raman microscopy, and atomic force microscopy (AFM) proved that InGaN-IL is very useful for the reduction of TDs and stress levels. High-quality growth of GaN using serpentine channel masks and further application of InGaN-IL is valuable for efficient optoelectronic devices. The simultaneous applications of both serpentine channel and IL are very useful for the reduction of TDs in SAG.

2. Methodology

2.1. Fabrication of substrate

Figure 1 represents the schematic diagram explaining the fabrication stages involved in patterned substrates of sapphire masked with a serpentine channel. First, a 100 nm-thick Si$_3$N$_4$ layer was deposited onto the sapphire substrate by low-pressure chemical vapor deposition (LPCVD) as a mask layer. Next, bottom windows were defined with standard photolithography and reactive-ion etching (RIE) technology with CHF$_3$ and argon (Ar). The RF power was set at 400 W. Then, SiO$_2$ was deposited at 250 °C by plasma-enhanced chemical vapor deposition (PECVD), followed by the 2nd Si$_3$N$_4$ film which was thicker than the 1st Si$_3$N$_4$ layer and also deposited by LPCVD. Standard photolithography and reactive-ion etching were applied to design the top windows of SCPSS with the same periodicity but with a lateral phase shift. In the end, the mid-layer of SiO$_2$ was removed by HF acid.
2.2. Growth
The growth of GaN is carried out in an MOCVD showerhead reactor. Trimethyl gallium (TMGa) and ammonia (NH$_3$) were the sources for Ga and N respectively and the mixture of H$_2$ and N$_2$ was used as carrier gas. Figure 2(a) from reference [8] depicts the modulated and ordinary ELOG techniques for GaN grown by SCPSS. The V/III ratio depends upon variation of NH$_3$ flow while the flow of TMGa is the same. The high and low V/III ratio was adjusted according to the design and shape of SCPSS. The flux of TMGa was 500 umol min$^{-1}$. The growths temperature and pressure were adjusted at 1078 °C and 300 Torr. During the growth of GaN, the InGaN-IL was added in closed stripes at 800 °C. The flux of trimethyl indium (TMIn) was 19 umol min$^{-1}$. Additionally, the conventional growth of GaN was grown on a flat sapphire substrate (FSS).

2.3. Measurements
Surface morphologies of GaN was studied by SEM-CL system FEI Quanta 200 F equipped with a Gatan MonoCL$_3$ system. AFM was performed on Bruker Dimension Icon System in tapping mode. TEM images were measured by FEI Tecnai F20. Since our growth is selective, therefore, samples were prepared by focus ion beam (FIB). The samples were developed by a focus ion beam (FIB) technique using Thermo Fisher Helios G4 UX. The working voltage for the FIB is 1–30 kV and the ion source is gallium (Ga). The thicknesses of FIB samples were 50 nm to 100 nm. The structure of the fabricated samples was examined on Bruker D8 high-resolution X-ray diffraction (HRXRD). Raman analysis was conducted by Raman system (Horiba-LabRAM HR800) with He-Ne laser source having a spot size 632.8 nm.

3. Results and discussions
3.1. Background
According to the schematic diagram of figure 1, the growth of GaN started from a lower window, after filling of windows, growth fronts merge from adjacent windows and produce defective areas. In figure 4(a) from reference [8], the etching-based SEM image indicated that coalescence growth of GaN is defective at meeting fronts because the pits are located in the coalescence areas. In the same way, figure 4(a) from reference [23] shows the plan-view of CL images from coalescence growth of GaN. It was observed that coalescence areas where two growth fronts meet appeared as dark bands. These dark bands are TDs acting as non-radiative recombination centers. It was supposed that if we stop the growth of GaN just before meeting-fronts, the window and wing areas can be used as a whole for micro-devices fabrication. Besides this, if we fabricate the windows at a large distance from each other’s, we can get a wide area free from TDs, which will expand its applications for the device. Therefore, SAG is introduced in the form of closed stripes and bar-shaped growth as shown in figure 2. Figure 2(a) shows plan-views of SEM images for closed stripes of GaN grown by the modified design of SCPSS. Figure 2(b) shows a cross-sectional view of the SEM image for closed stripes grown by SCPSS. The steps of modulated and ordinary ELOG were completed according to figure 2(a) from reference [8]. The growth parameters (V/III ratio, TMGa, and NH$_3$) and steps for 1st, 2nd, and 3rd ELOGs were changed.
according to the design of SCPSS. SEM images show that the surface of stripes is smooth and crack-free over the whole SCPSS. To further investigate the crystal quality of closed stripes, the TEM analysis was conducted at three typical areas of SCPSS as shown in figure 3. TEM analysis is conducted at region A, region B, and region C as shown in figures 3(a)–(c) respectively. In region A, TDs move upwards and they were blocked by overhanging masks while remaining TDs were bent along horizontal direction because of image forces [24–26]. However, in region B and region C, TDs have only horizontal configurations. Such horizontal TDs (HDs) do not intersect the surface of GaN-based devices so; these TDs do not threaten the device performance [7]. In previous cases, TDs react with each other’s and make dislocation loops while, in some cases, TDs terminate inside the window area. Therefore, TDs were controlled by blocking and bending as well as by dislocation-dislocation reactions [27, 28]. Since TEM analysis is based on a small area, therefore further investigation on TDs is carried out by CL.

Based on the TEM discussion, the control of TDs during growth of closed stripes is illustrated according to our proposed model from figure 4. Generation of TDs is represented by black lines. Figure 4 show that some TDs move upwards and they are blocked by the mask while some TDs bent due to image forces. In the same way, some TDs react with others TDs and the formation of dislocation loops further control TDs. The remaining TDs survived and move upwards by making two 90° angles, however, the InGaN–IL block TDs.

To further investigate the crystal quality of closed stripes, CL analysis is conducted as shown in figure 5. Figure 5(a) shows the plan-view of CL image for conventional growth on FSS. Figures 5(b) and (c) show the plan-view and cross-sectional view of CL images for pattern growth before InGaN–IL respectively. The comparison between pattern growth and conventional growth shows that pattern growth is superior because conventional growth of GaN is dominant with non-radiative recombination centers. However, the strained layers of closed
stripes are relaxed and generate clusters of black lines (TDs) on the stripes areas. During a long growth time, the stress has been built in the GaN in closed stripes. After stress relaxation, many TDs originate from the interface and glide in the m-plane of GaN [19]. Figure 5 (c) shows the cross-sectional view of the CL image where back lines originate from the interface of GaN. These black lines intersect each other strips while they disappear at the center where all stripes combine. To further improve the crystal quality of closed stripes, the InGaN-IL was added during growth. The growth temperature of closed stripes was ramped down and InGaN-IL was added at 800 °C. The closed stripes were grown with InGaN-IL as shown in the schematic diagram in figure 5 (d).

Figures 5 (e) and (f) show the plan-view and cross-sectional view of CL images for closed stripes grown with InGaN-IL, respectively. It is clear that the addition of InGaN-IL in closed stripes further improves the crystal quality of GaN.

To further investigate the effects of InGaN-IL, the Raman analysis is conducted as shown in figure 6. The compressive stress was estimated according to the following relationship.

\[ \sigma = \frac{\Delta \omega}{4.3} \text{cm}^{-1}\text{GPa}^{-1} \]

Here, the \( \Delta \omega \) is the shift in Raman peaks. The standard E2 (high) peak of GaN for the strain-free GaN crystal is at 567.5 cm\(^{-1}\) [28, 29]. Before Raman line-scan, compressive stress was compared between conventional and patterned growth as shown in figure 6(a). The Raman shift between conventional and patterned growth is 570.921 cm\(^{-1}\) and 569.400 cm\(^{-1}\) respectively. The compressive stress between conventional and patterned growth is 0.795 GPa and 0.441 GPa respectively.

Raman line-scan was conducted along the window to wing line as shown in the figure 5(b) where the positions of Raman line-scan are marked by a white arrow. Figure 5(c) shows that stress is rising towards the window area. Figure 6(d) shows the sudden falls of compressive stress distribution in the closed stripes grown with InGaN-IL because of reduction of TDs. The compressive stress depends upon the density of TDs and the fall of compressive stress is due to the reduction of TDs [30]. It is concluded that stress level in closed stripes is reduced efficiently by InGaN-IL because TDs are reduced. Results of Raman line-scans are consistent with plan-view and cross-sectional view of CL images. The maximum stress in closed stripes before and after InGaN-IL is 0.250 GPa and 0.187 GPa respectively.

To further investigate the quality of GaN, HRXRD measurements were carried out and results of XRD rocking curves are incorporated in the supplementary material (available online at stacks.iop.org/MRX/9/045901/mmedia). The CL images show that nonradioactive recombination in closed stripes is reduced significantly while HRXRD show that the density of TDs in pattern growth is higher than conventional growth.
The results of HRXRD are incorporated in supplementary material. Different hypotheses are considered to explain inconsistency between HRXRD and CL images. It is assumed that due to strain relaxation, the clusters of TDs are produced in pattern growth, therefore, FWHM increases due to larger density of TDs. However, the addition of InGaN-IL further control TDs but values of FWHM in pattern growth are still larger than conventional growth. It is further assumed that a large X-ray beam with has larger penetration depth provides better results about dislocation density. In CL, the penetration depth depends upon the voltage of CL and due to the low voltage of CL, the results of HRXRD are better than CL. However, this assumption is not acceptable because the voltage of CL was increased from 5 kV to 30 kV. The further high voltag CL images with larger CL scales from supplementary material also prove that TDs in closed stripes are lower than pattern growth. According to [31], the tilt in uncoalescence growth of GaN also increases the FWHM. As lateral growth fronts of GaN are free-standing relative to the seeds GaN supported by sapphire meseas. The other is that the thermal expansion coefficient of GaN is smaller than that of sapphire. When samples of GaN are cooled down from the growth temperature to the room temperature, the compressive stress in the wing area is nearly free. As a result, the wing area is bent down towards $\langle 11\overline{2}0 \rangle$ GaN direction and tilt is produced. The tilt angle does not only depend upon the bending of wing area but also depends upon the density of TDs, vinical angle, strain relaxation, and filling factors of the substrate [32–35]. Therefore, the broadness of FWHM of rocking curves depends upon different factors and it is the subject of further investigation. In addition, growth is selective, therefore, there are three typical regions known as window area, wing area, and coalescence area. The distribution of TDs in these areas is different. The coalescence area is defective whereas, the wing area shows high quality. In the same way, the initial layers of GaN inside the channel of SCPSS are highly defective while top regions of GaN layers show high-quality growth. In the same way, the central areas where all stripes are met show high-quality growth. By using CL, we can easily target these areas. However, by using HRXRD, we could not target these areas. Therefore, analysis of TDs based on CL images is better than HRXRD. Figures 7(a)–(c) compares the CL images between conventional and pattern growth. The nonradiative recombination rates is reduced at the center of closed stripes and dots are countable. Therefore, the density of TDs for patterned growth before and after InGaN-IL is in the order of $2 \times 10^{9}$ cm$^{-2}$ and $2.1 \times 10^{7}$ cm$^{-2}$ however, the density of TDs for conventional growth is very high.
and counting of dots is not possible. Figures 7(d)–(f) indicate $10 \times 10^8 \mu \text{m}^2$ AFM-scans for conventional growth and patterned growth. The RMS value of surface roughness for conventional growth was 2.26 nm. Root mean square value of surface roughness (RMS) for closed stripes without InGaN-IL is 1.79 nm. After the addition of InGaN-IL, the surface morphology of closed stripes is further improved and the RMS value of surface roughness further reduces to 0.616 nm. The further AFM results are incorporated in the supplementary material. The straight, parallel and long crystallographic steps prove that the growth of closed stripes is step by step and layer by layer. The layer by layer and step flow growth proves high-quality growth of GaN.

The following table compares the quality of three samples based on the density of TDs, stress level, and RMS values of surface roughness. The density of TDs in sample A is not countable because nonradiative recombination is the highest. However, density of sample B and sample C is countable at the center where all patches are combined.

| Samples names | Density of TDs ($\text{cm}^{-2}$) | Stress (GPa) | RMS-Values (nm) |
|---------------|-----------------------------------|--------------|-----------------|
| A             | Not countable                     | 0.795        | 2.26            |
| B             | $2 \times 10^8 \text{ cm}^{-2}$   | 0.250        | 1.79            |
| C             | $2.1 \times 10^7 \text{ cm}^{-2}$ | 0.187        | 0.616           |

4. Conclusion

High-quality GaN is achieved by patterned sapphire substrate masked with a serpentine channel mask. The comparative studies between conventional and patterned growth based on morphological, structural, and optical characterizations show that the crystal quality of closed stripes is higher than the conventional growth of GaN grown by FSS. Efficient prevention of TDs and strain relaxation by serpentine channel mask technology is very helpful to further improve the performance of GaN-based devices. The results of SEM and AFM images show very smooth morphology. The analysis of TDs by TEM shows that TDs significantly reduced, however, the strained layers of closed stripes are relaxed and produce many TDs. Raman, CL, and AFM analysis show that the addition of InGaN-IL in closed stripes further improves the quality of GaN.
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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Zheng Z, Zhang L, Song W, Feng S, Xu H, Sun J, Yang S, Chen T, Wei J and Chen K J 2021 Gallium nitride-based complementary logic integrated circuits Nat. Electron. 4 593–603
[2] Wang F, Chen W, Xu X, Sun R, Wang Z, Xia Y, Xin Y, Liu C, Zhou Q and Zhang B 2021 Simulation study of an ultralow switching loss GaN Gate HEMT with dynamic charge storage mechanism IEEE Trans. Electron Devices 68 175–83
[3] Wang Z, Wang S, Zhang Z, Wang C, Yang D, Chen X, Wang Z, Cao J and Yao Y 2019 A High-Performance Tunable LED-Compatible Current Regulator Using an Integrated Voltage Nanoens ter 66 1917–23
[4] Kundakçı M, Mantarci A and Erdoğan E 2017 Growth and characterization of GaN thin film on Si substrate by thermionic vacuum arc (TVA) Mater. Res. Express 4 2–8
[5] Ramesh C, Tyrapi P, Mauraya A K, Senthil Kumar M and Kushvaha S S 2019 Structural and optical properties of low temperature grown single crystalline GaN nanorods on flexible tungsten foil using laser molecular beam epitaxy Mater. Res. Express 6 085919
[6] Zou J, Zeng L and Li Y 2019 Electronic structure and optical properties of Lu, As doped GaN from first-principles study Mater. Res. Express 6 126304
[7] Zhang W et al 2013 Dislocation reduction through nucleation and growth selectivity of metal-organic chemical vapor deposition GaN J. Appl. Phys. 113 144908
[8] Li Q, Li L, Zhang W, Jiang S, Yin X, Yan T, Yang W, Chen W and Hu X 2016 Dislocation reduction and stress relaxation of GaN and InGaN multiple quantum wells with improved performance via serpentine channel patterned mask ACS Appl. Mater. Interfaces 8 21480–9
[9] Zhu Y, Hu T, Wang M, Li Y, Ge M, Guo X, Deng H and Chen Z 2022 Characterization of the micro-structural properties of InAlN/ GaN epi-layer grown by MOCVD Crystals. 12 203
[10] Khan M S A, Liao H, Yu G, Iqbal I, Lei M, Lang R, Mi Z, Chen H, Zong H and Hu X 2021 Reduction of threading dislocations in GaN grown on patterned sapphire substrate by using serpentine channel MS Material Sci. in Semiconductor Processing 134 106013
[11] Dash A, Sharma A, Jain S K, Patra B S K, Gundimeda A, Mallik S and Gupta G 2022 Influence of current conduction paths and native defects on gas sensing properties of polar and non-polar GaN J. Alloys Compd. 898 162808
[12] Zheleva T S, Smith S A, Thomson D B, Linthicum K J, Rajagopal P and Davis R F 1999 Pendeo-epitaxy: a new approach for lateral growth of gallium nitride films J. Electron. Mater. 28 3–8
[13] Pollaertd D J, Provencio P P, Koleske D D, Mitchell C C, Allerman A A, Missert N A and Ashby Sandia C I H 2003 Cantilever epitaxy of GaN on sapphire: further reductions in dislocation density national laboratories Albuquerque, NM 743 18
[14] Fang X L, Wang Y Q, Meida H and Mabahanz S 2004 Reduction of threading dislocations in GaN layers using in situ deposited silicon nitride masks on AlN and GaN nucleation layers Appl. Phys. Lett. 84 484–6
[15] Sager A, Feenstra R M, Inoki C K, Kuan T S, Fu Y, Moon Y T, Yun F and Morook H 2005 Dislocation density reduction in GaN using porous SiN interlayers Phys. Status Solidi Appl Mater. Sci. 202 722–6
[16] Benamara M, Lillental-Weber Z, Kellermann S, Swider W, Washburn J, Mazur J and Bourret-Courchesne E D 2000 Study of high- quality GaN grown by OMVPE using an intermediate layer J. Cryst. Growth 218 447–50
[17] Tao Y B, Yu J, Yang Z Y, Ling D, Wang Y, Chen Z Z, Yang Z J and Zhang G Y 2011 Evolution and control of dislocations in GaN grown on cone-patterned sapphire substrate by Metal Organic Vapor Phase Epitaxy J. Cryst. Growth 315 183–7
[18] Wei T, Zong H, Jiang S, Yang Y, Liao H, Xie Y, Wang W, Lij, Tang J and Hu X 2018 High-quality GaN epitaxially grown on Si substrate with serpentine channels Superlattices Microstruct 118 284–8
[19] Okada N, Ishikawa A, Yamane K, Tadatomo K, Jahn U and Grahn H T 2014 Generation of dislocation clusters by glide m-planes in semipolar GaN layers, Phys. Status Solidi Appl Mater. Sci. 211 736–9
[20] Xue J S, Hao Y, Zhang J C and Yang L A 2010 Effect of growth temperature of AlN interlayers on the properties of GaN epilayers grown on c-plane sapphire by metal organic chemical vapor deposition Phys. Status Solidi Curr. Top. Solid State Phys. 7 2371–3
[21] Moram M A, Zhang Y, Kappers M J, Barber Z H and Humphreys C J 2007 Dislocation reduction in gallium nitride films using scandium nitride interlayers Appl. Phys. Lett. 91 8 11
[22] Rossoon U, Hintel F, Riedel N, Lahmann S, Blasing J, Kroest A, Ade G, Hinze P and Hangleiter A 2003 Influence of low-temperature interlayers on strain and defect density of GaN Layers J. Cryst. Growth 248 528–32
[23] Wei T, Zong H, Jiang S, Yang Y and Liao H 2018 Superlattices and microstructures high-quality GaN epitaxially grown on Si substrate with serpentine channels Superlattices Microstruct 118 284–8
[24] Kuwano N, Horibuchi K, Miyake H and Hiramatsu K 2000 TEM analysis of threading dislocations in ELO-GaN grown with controlled facet planes Mater. Res. Soc. Symp. – Proc. 639, 1159
[25] Gradečak S, Stadelmann P, Wagner V and Ilegems M 2004 Bending of dislocations in GaN during epitaxial lateral overgrowth Appl. Phys. Lett. 85 4648–50
[26] Tanaka S, Honda Y, Sawaki N and Hibino M 2001 Structural characterization of GaN laterally overgrown on a (111)Si substrate Appl. Phys. Lett. 79 955–7
[27] Romano L T, Krusor B S and Molnar R J 1997 Structure of GaN films grown by hydride vapor phase epitaxy Appl. Phys. Lett. 71 2283–5
[28] Xu S R, Li P X, Zhang J C, Jiang T, Ma J J, Lin Z Y and Hao Y 2014 Threading dislocation annihilation in the GaN layer on cone patterned sapphire substrate J. Alloys Compd. 614 360–3
[29] Wei T, Liao H, Jiang S, Yang Y, Zong H, Li J, Yu G, Wen P, Lang R and Hu X 2019 Stress study of GaN grown on serpentine-channels masked Si(111) substrate by MOCVD Superlattices Microstruct 130 554–9
[30] Jiang T, Xu S R, Zhang J C, Xie Y and Hao Y 2016 Spatially resolved and orientation dependent Raman mapping of epitaxial lateral overgrowth nonpolar a-plane GaN on r-plane sapphire Sci. Rep. 6 1–8
[31] Wang J, Guo L W, Jia H Q, Xing Z G, Wang Y, Chen H and Zhou J M 2006 Lateral epitaxial overgrowth of GaN films on patterned sapphire substrates fabricated by wet chemical etching Thin Solid Films 515 1727–30
[32] Einfeldt S, Roskowski A M, Preble E A and Davis R F 2002 Strain and crystallographic tilt in uncoalesced GaN layers grown by maskless pendeoepitaxy Appl. Phys. Lett. 80 953–5
[33] Fini P, Marchand H, Ibbetson J P, DenBaars S P, Mishra U K and Speck J S 2000 Determination of tilt in the lateral epitaxial overgrowth of GaN using X-ray diffraction J. Cryst. Growth 209 581–90
[34] Shen X Q, Matsuhata H and Okumura H 2005 Reduction of the threading dislocation density in GaN films grown on vicinal sapphire (0001) substrates Appl. Phys. Lett. 86 10–3
[35] Kisielowski C et al 1996 Strain-related phenomena in GaN thin films Phys. Rev. B - Condens. Matter Mater. Phys. 54 17745–53