Growth of GaN on \{1235\}-like Facets of Patterned Sapphire Substrate

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Abstract

GaN has been grown on wet-etched patterned sapphire substrate (PSS) by metal-organic chemical vapor deposition. It has been found that GaN was initiated not only from bottom c-facet but also from E (1235) facets of hexagonal patterns/pyramids. In this study, a vacancy-PSS on c-plane sapphire was used to investigate the growth of GaN on the E-like facets (E1 and E2) of distorted pyramids. The results show that the orientation relationship between E1-GaN and sapphire is (TT26)_{GaN} // (0110)_{sapphire} and [1127]_{GaN} // [1120]_{sapphire}. At the same time, that between E2-GaN and sapphire is (0114)_{GaN} // (3306)_{sapphire} and [0223]_{GaN} // [1120]_{sapphire}.

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Light-emitting diodes (LEDs) have been widely used in a variety of applications. Patterned sapphire substrate (PSS) has been developed to improve internal quantum efficiency (IQE) and light extraction efficiency (LEE) of GaN-based LEDs. There are two methods to fabricate PSSs: (1) dry etching and (2) wet etching. When growing on wet-etched PSS, GaN crystal not only initiated from bottom c-facet but also from E (1235) facet of hexagonal pyramids/patterns. The GaN grown on the E-facets was semi-polar oriented.

Besides, GaN quality could be improved by reducing the unpatterned bottom c-plane area from 47.5% to 9.6% of the total wafer areas. This is because most of the GaN growth was initiated from bottom c-planes. As growth time increased, GaN epilayers on the c-plane covered these pyramids causing the threading dislocation to bend toward the patterns. As a result, threading dislocation density would decrease with the bottom c-plane areas. However, further decreasing in bottom c-plane areas makes epitaxy of GaN film very difficult. In our previous study of the evolution of bottom c-planes, the vacancy-mask is illustrated in Fig. 1a. Sample was etched with 98 wt% H2SO4:85 wt% H3PO4 (3:1) solution at 270°C. The vacancy-mask is easy to confirm that the zone axis of sapphire in Fig. 2d is [11-20], while that of E2-GaN is [02-21]. The orientation relationship between E1-GaN and sapphire is (TT26)_{GaN} // (1100)_{sapphire} and [1127]_{GaN} // [1120]_{sapphire}. At the same time, that between E2-GaN and sapphire is (0114)_{GaN} // (3306)_{sapphire} and [0223]_{GaN} // [1120]_{sapphire}.

Transmission electron-microscopy (TEM) was used to verify the nature of these GaNs. The cross-sectional TEM specimens were prepared by focus ion beam (FIB) cutting along [1100]_{sapphire} (line-b and line-c) as shown in Fig. 2a. The related TEM images are shown in Figs. 2b and 2c. To identify the crystallographic relationships between GaNs and sapphire substrate, selected-area diffraction patterns (SADPs) were taken from GaN crystals and PSS (Figs. 2d–2f). All these grown GaNs were identified as Wurtzite structure.

As shown in Figs. 2b and 2c, the SiO2 etching mask (O) is observed on the top of the sapphire substrate. C-GaN was grown on the bottom-c facet, while E2-GaN and E1-GaN were on the sidewall facets. The thickness of C-GaN was 0.963 μm, which was larger than that of E1-GaN (0.405 μm) and E2-GaN (0.411 μm).

The crystallographic relationship between C-GaN and sapphire (Figs. 2c and 2e) is established as (0001)_{GaN} // (0001)_{sapphire} and [1010]_{GaN} // [1120]_{sapphire}. This orientation relationship is usually seen in the case of a GaN epitaxially grown on a c-plane sapphire.

SADPs (Fig. 2d) taken from the interfacial area corresponding to the circle-d in Fig. 2b are used to investigate the orientation relationship between E2-GaN, sapphire and interface. As the TEM specimen was cut parallel to the flat edge of sapphire corresponding to a-plane, it is easy to confirm that the zone axis of sapphire in Fig. 2d is [1120], while that of E2-GaN is [0221]. The orientation relationship between E2-GaN and sapphire is (0114)_{GaN} // (3306)_{sapphire} and [0223]_{GaN} // [1120]_{sapphire}, which are similar to our previous studies of the GaNs growing on E (1235) facets.

However, the orientation relationship between E1-GaN and sapphire was different from that between E2-GaN and sapphire. SADPs (Fig. 2f) taken from the circle-f in Fig. 2c were used to investigate their relationship. The zone axis of sapphire is still [1120], while that of E1-GaN is changed from [0221] to [1127]. The orientation relationship between E1-GaN and sapphire is (TT26)_{GaN} // (1102)_{sapphire} and [1127]_{GaN} // [1120]_{sapphire}. A series of experimental and simulated SADPs were used to double-confirm the zone axis ([1127]) of E1-GaN. Sample has been further tilted from [1127] to other 4 zone axes, [1120], [5273], [2243] and [3037] (not shown). The tilting angles between zone axes

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Figure 1. (a) Schematic illustrations of vacancy-mask. (b) and (c) are SEM images of PSS surfaces after etching at 270°C for 10 min.

are all match the simulated angles. Besides, the enlargement image of E1-GaN/sapphire interface is shown in Fig. 3a, which shows the initiations of dislocations, dark contrast, from the growing surface/interface. The related high-resolution transmission electron microscopy (HRTEM) image is shown in Fig. 3b. The inverse fast Fourier transform (IFFT) was adopted for further analyzes this region. Figure 3c displays the processed IFFT image of Fig. 3b, which shows the interface of (TT26)GaN // (1102)sapphire and (1100)GaN //

Figure 2. (a) SEM images of C-GaN, E1-GaN and E2-GaN grown on sapphire substrate. (b) and (c) are bright-field cross-section TEM images from (a) indicated by line-b and line-c. (d), (e) and (f) are SAD patterns taken from (b) and (c), respectively. These patterns are from interface regions of E2-GaN/sapphire [(d)], E1-GaN/sapphire [(e)] and C-GaN/sapphire [(f)].
Figure 3. (a) High magnification TEM image of E1-GaN from Fig. 2c. (b) HRTEM image of E1-GaN/ sapphire interface from (a) indicated by dashed frame. (c) IFFT image of (b) (E1-GaN/ sapphire interface). The d-spacing of (1¯104)sapphire is 2.720 Å. The d-spacing of (1¯100)GaN and (1¯104)sapphire is 2.720 and 2.550 Å, respectively. Their mismatch ratio is about 6.25%. Thus, the misfit dislocation marked as “⊥” was observed at the interface between GaN and sapphire as shown in Fig. 3c.

Summary

Wet-etched PSS has been employed to improve the performance of GaN-based LEDs. It has been found that GaN was initiated not only from bottom c-facet but also from E {1235} facets of hexagonal patterns/pyramids. When vacancy dot array SiO2 mask was used, the shape of pyramid was distorted. New E-like facets (E1 and E2) were created. The orientation relationships between GaNs and sapphire were investigated. The relationship between E1-GaN and sapphire is (TT26)GaN // (1¯102)sapphire and [112T]GaN // [1120]sapphire. At the same time, that between E2-GaN and sapphire is (0114)GaN // (3306)sapphire and [0221]GaN // [1120]sapphire.

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