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N-face GaN (000-1) Films with Hillock-Free Smooth Surfaces Grown by Group-III-Source Flow-Rate Modulation Epitaxy

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Abstract

We demonstrate group-III-source flow-rate modulation epitaxy for growing N-face GaN (000-1) films with smooth surfaces, wherein the flow-rate of group-III sources are sequentially modulated under a constant supply of NH_3. We successfully formed hillock-free surfaces of N-face GaN (000-1) films over almost the whole sample area (4 x 4 mm^2) on GaN bulk substrates.

1. Introduction

N-face (000-1) group-III-nitride films show various advantages over conventional group-III-face (0001) ones. The inverse direction of their polarization field facilitates new device topologies in AlGaN/GaN field effect transistors [1, 2]. In addition, N-face (000-1) can prevent the evaporation of nitrogen atoms from the growing surface since a nitrogen atom is bound with three underlying group-III atoms. N-face InN (000-1) films can therefore be grown at a growth temperature 100°C higher than In-face InN (0001) ones [3].

However, a serious problem in N-face GaN (000-1) films has been a high density of hillocks on the film surface. The hillock formation is believed to be due to the poor surface migration of adatoms on the N-face (000-1) surface [4]. Recently, we proposed group-III-source flow-rate modulation epitaxy (FME), in which the flow-rate of the group-III-source is sequentially modulated, while the group-V source (NH_3) is supplied continuously at a constant flow rate. We have successfully reduced hillocks of N-face GaN (000-1) films using sapphire substrates, since the surface migration of Ga adatoms is enhanced in group-III-source FME [5]. In this study, we grew N-face GaN (000-1) films on N-face GaN (000-1) bulk substrate by group-III-source FME and successfully obtained hillock-free surfaces with a step-and-terrace structure over the whole surface area.

2. Experimental

GaN films were grown on N-face GaN (000-1) bulk substrates by metalorganic vapor phase epitaxy (MOVPE). The size of GaN bulk substrates was approximately 4 x 4 mm^2. The misscut angle of the substrates was approximately 0.3^o toward <1-100> and the threading dislocation density was less than $5x10^6$ cm^{-2}. The source gases were trimethylgallium (TMG), triethylgallium (TEG), and NH_3 and the carrier gas was purified H_2. NH_3 was continuously supplied with the flow rate of 0.067 mol/min. On the other hand, the group-III source, TMG or TEG, was supplied at higher or lower flow rate as shown in Fig. 1. The durations of the higher and lower flow-rate periods for one cycle were 1 and t s, respectively. The *t* value was varied from 0 to 10 s. The lower-flow-rate supply of the group-III source during the migration enhancement period was required in order to prevent desorption of Ga from the growing surface. In other words, neither deposition nor etching of GaN occurs during the period of the lower flow rate. Totally, 900 cycles were repeated at the growth temperature of 1015°C, resulting in the total film thickness of approximately 450 nm [5].

3. Results and Discussion

Figure 2 shows optical micrographs of N-face GaN (000-1) films grown by group-III-source FME. Hillocks, including hexagonal pyramids and plates, are observed in the samples for t = 0 and 2 s. The normal vector of every side of the hillocks is parallel to the [1-100] direction of GaN, which indicates a common preferential orientation in the GaN films. On the other hand, hillock-free surfaces are achieved over almost the whole sample area (4 x 4 mm^2) for t longer than 5 s. As shown in Fig. 3, the density of hillocks on the surface decreases drastically with increasing t. Note that the hillock density is comparatively low (560 cm^{-2}) even for t = 0, since the GaN films were grown on GaN bulk substrates with low dislocation density. Figure 4 shows an AFM image of the film surface for t = 10 s. The sample has a smooth surface with a step-and-terrace structure along the [11-20] direction. The root mean square (RMS) surface roughness is 0.39 nm, which is almost the same as that of the GaN bulk substrate. The surface exhibits mainly two-monolayer (~0.52 nm) steps, and the average width of the terraces is 82 nm. No step bunching is observed on the surface. The misorientation angle of the sample is estimated to be 0.36^o from the terrace width. This value is close to the misorientation of the substrate (0.3^o), which demonstrates that the step-flow growth mode is promoted by using group-III-source FME.

The reason for the decrease in hillock density by group-III-source FME is considered to be enhancement of the surface migration of Ga atoms under low surface supersaturation during the lower Ga supply period t. We have confirmed that a hillock originates from a screw-type dislocation and forms a growth spiral [6]. The spiral growth rate of GaN rapidly decreases with decreasing surface supersaturation, while the step-flow growth rate decreases linearly [7]. Therefore, under low surface supersaturation, the spiral growth rate can be lower than the step-flow growth one so that hillock formation is suppressed.

4. Conclusions

We successfully grew hillock-free N-face GaN (000-1) films over almost the whole sample area (4 x 4 mm^2) on GaN bulk substrates by group-III-source FME. Enhancement of the surface migration of Ga atoms under low surface supersaturation during the lower Ga supply period would explain the decrease in the hillock density with group-III-source FME.

References

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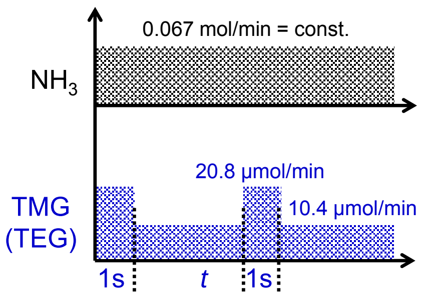

Fig. 1: Time sequences of group-III-source FME.

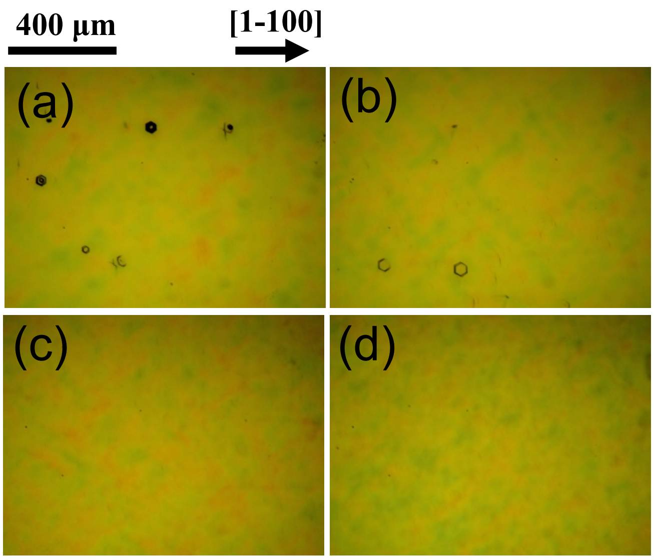

Fig. 2: Optical micrographs showing the influence of duration t on the surface morphologies of N-face GaN (000-1) films grown by group-III-source FME. The t values are (a) 0, (b) 2, (c) 5, and (d) 10 s, respectively.

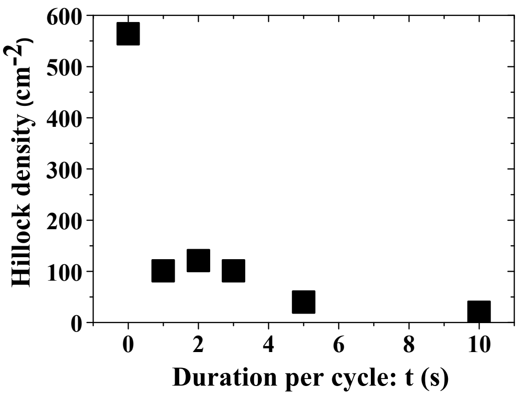

Fig. 3: Hillock density on N-face GaN (000-1) film surfaces plotted as a function of t in group-III-source FME.

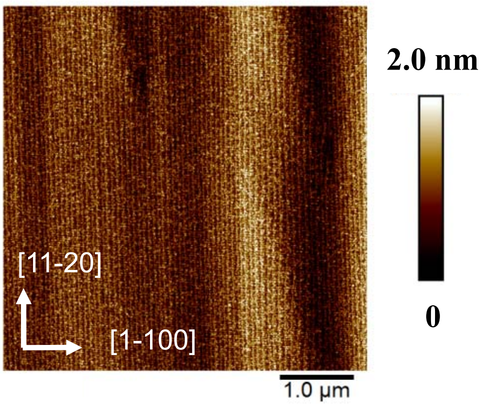

Fig. 4: AFM image of the N-face GaN (000-1) film grown by group-III-source FME for t = 10 s.