Anisotropic epitaxial lateral growth in GaN selective area epitaxy

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Epitaxial lateral mask overgrowth which occurs during GaN selective epitaxy has been studied using linear mask features. The lateral growth varies between its maximum and minimum over a 30° angular span and exhibits hexagonal symmetry. Vertical growth follows an opposite trend, with lateral growth maxima, and vertical growth minima occurring for lines parallel to the GaN ⟨10•0⟩. Large variations in the lateral growth are also obtained through variations in the growth temperature and NH_3 flow. Under proper growth conditions, lateral to vertical growth rate ratios of up to 4.1 can be achieved, resulting in significant lateral mask overgrowth and coalescence of features without excessive growth times. [S0003-6951(97)02635-1]

The earliest reports of selective epitaxy of III–V semiconductors discuss growth rate anisotropies and mask overgrowth.[1,2] Lateral mask overgrowth has been exploited for defect reduction in several epitaxial thin films, a process referred to as epitaxial lateral overgrowth (ELO).[3,4] This process has also been used to produce removable epitaxial layers from a reusable substrate.[5] Growth rate anisotropies which occur during GaN selective epitaxy cause pyramid structures to result from growth in small two-dimensional mask features.[6,7] The pyramid structures are bounded by slow-growth $(1\underline{1}01)$ sidewalls, with only convex edges. Growth on the basal GaN planes occurs rapidly compared to growth on the inclined planes prior to pyramid completion under all of the conditions studied.

Growth from linear mask openings allows the study of orientation-dependent lateral growth without favoring the development of slow-growth facets. The growth[8] and optical characterization[9] of GaN by selective epitaxy using linear mask features has been previously reported. However, the effect of line orientation on the morphology of resulting GaN growth has not yet been investigated. In this letter we will discuss our results of orientation-dependent selective epitaxy of GaN, and the effect of growth parameter variation on the lateral (in-plane) growth rate anisotropies. These results may represent an opportunity for dislocation reduction in GaN through the ELO process.

Base GaN films for this study were obtained using atmospheric pressure metalorganic chemical vapor deposition (MOCVD). Growth conditions for these films have been published elsewhere.[10] Plasma-enhanced chemical vapor deposition (PECVD) or electron beam evaporation was then used to deposit 200 nm thick SiO_2 films on the GaN. These films were patterned using standard photolithographic procedures and etching with hydrofluoric acid (HF). A short (~8 s) dip in dilute HF was used immediately prior to regrowth in order to clean the growth surface. Selective epitaxy of GaN was performed by MOCVD using trimethyl gallium (TMGa) and ammonia (NH_3) precursors, and hydrogen as the carrier gas, at 76 Torr reactor pressure. Growth temperatures were varied between 980 and 1080 °C, and ammonia flows were varied between 0.089 and 0.356 mole/min. For all regrowth experiments, TMGa flows of 18.35 μmole/min were used, which would result in nominal planar growth rates of 1 μm/h. For experiments in which ammonia flow was varied, total flow was maintained using variations of the hydrogen flow. GaN line thicknesses were obtained using DEKTAK profilometry. GaN linewidths were obtained from field-emission (SEM) images using the public domain software, NIH Image,[11] on a Power PC computer.

In our previous study, we found that the growth on GaN pyramid sidewalls using selective epitaxy was maximized at conditions of high temperature and high ammonia flow.[6,12] The orientation dependence of GaN growth rates using linear mask features was studied under these conditions ($T = 1060$ °C, 76 Torr, $NH_3 = 0.3$ mole/min) using a large star pattern. This pattern consists of mask opening line pairs, 5 mm long, oriented at 4° rotational increments. Figure 1 contains the resulting GaN regrowth line widths and thicknesses over an angular span of 90°. Lines oriented parallel to the ⟨10•0⟩ GaN directions have triangular wedge cross sections, with sidewalls similar to hexagonal pyramids, and no remaining basal surface. This morphology is a result of a low lateral to vertical growth rate ratio. Lines oriented parallel to the ⟨21•0⟩ GaN orientation, however, are characterized by high lateral to vertical growth rate ratios and so the width of the exposed basal surface actually increases with growth time. These behaviors exhibit hexagonal symmetry, with a

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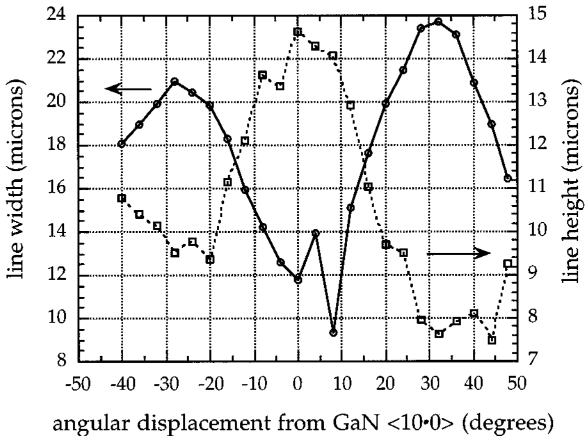

FIG. 1. Plot of GaN linewidth and height as a function of orientation following selective regrowth under conditions of high temperature and high ammonia flow.

30° angular span between the lateral and vertical growth maxima and minima, as illustrated in Fig. 1.

Further experiments were performed using variations of temperature and ammonia flow. These experiments utilized a second selective epitaxy mask pattern consisting of a star feature with lines at 30° increments, parallel to the ⟨10•0⟩ and ⟨21•0⟩ directions, surrounded by large masked regions. The star consists of six consecutive lines of 5 μm opening width, and six consecutive lines of 10 μm width. The results indicate that growth rate anisotropy is a strong function of both the temperature and ammonia flow. Figure 2(a) contains a SEM image of the star feature with the greatest anisotropy, obtained using the maximum ammonia flow. The original mask openings are visible through the regrown GaN. Figure 2(b) contains a cross-sectional SEM image of a line oriented parallel to the ⟨21•0⟩ under identical conditions. The lateral to vertical growth rate ratio for this line is approximately 4.1 for this growth.

The in-plane growth rate anisotropy can be evaluated using the differences in linewidths at the two orientations. Figure 3 contains plots of the linewidth difference as a function of temperature and ammonia flow. As the ammonia flow is decreased, the difference approaches zero, indicating that the lateral mask overgrowth rate is group *V* dependent. These results are consistent with our earlier studies in which we found that self-limited growth of GaN hexagonal pyramids can be achieved at low ammonia reactor flow.[12] As the temperature is decreased with constant ammonia flow, the difference also decreases significantly. Additional experiments using patterns consisting of arrays of linear mask openings indicate that as the pattern fill ratio, defined as the ratio of mask opening area to total area, increases, the rate of lateral growth decreases.

The slow growth rate of the GaN$(1\bar{1}01)$ surface is the predominant feature of GaN selective epitaxy. Previous studies have shown that the growth on GaN pyramid sidewalls can be increased or essentially eliminated through variations in the growth parameters.[6,12] The trends which occur for the growth of linear features are similar. Lines oriented parallel to GaN ⟨21•0⟩, however, exhibit lateral growth rate variations of much greater magnitude. These high lateral growth

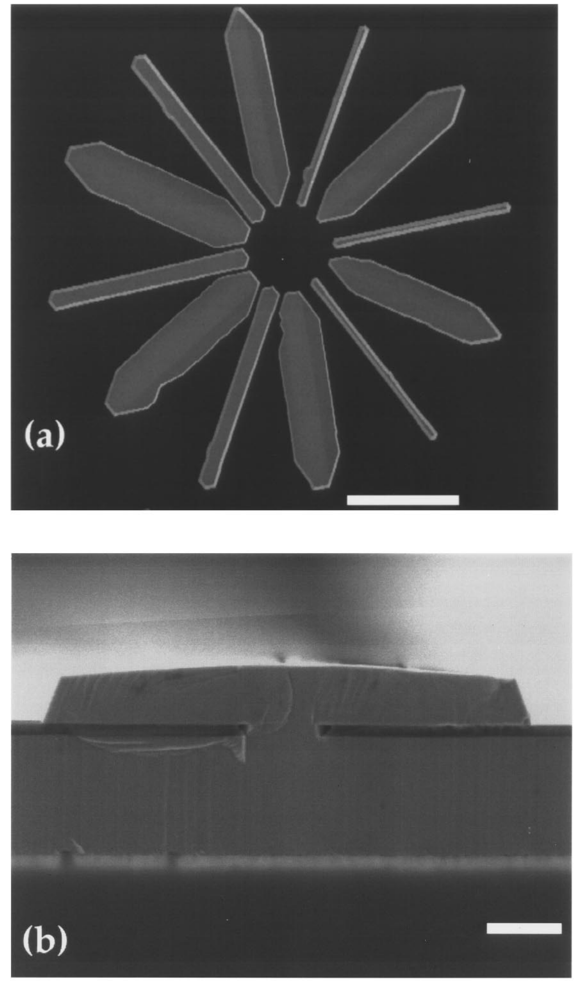

FIG. 2. (a) Star feature illustrating in-plane anisotropic growth (bar=50 μm). (b) Cross-sectional SEM image of a line oriented parallel to the GaN ⟨21·0⟩ (bar=1 μm).

rates are obtained only when the orientation of the line does not allow the direct formation of the stable facets. Near the line ends, the growth front may decompose into $(1\bar{1}01)$ planes, as is evident in Fig. 2(a). This occurs, as with the small pyramid structures, without the formation of concave edges between $(1\bar{1}01)$ planes. Using (111)B GaAs substrates, Tausch and Lapierre reported that GaAs selective epitaxy also resulted in hexagonal structures, with mask overgrowth occurring more rapidly in the ⟨110⟩ directions than the ⟨211⟩ directions.[1] They were also able to achieve significant mask overgrowth through the use of straight, properly oriented lines.

Asai explained trends in the in-plane growth rate anisotropy from GaAs round mesa structures based on the atomic arrangement.[13] The incorporation probability of Ga was related to the density of dangling bonds at the step edge, a function of the crystallographic orientation. The dangling bond density was also related to the availability of As at the step edge, a factor which is dependent on both orientation and V/III ratio. No directly analogous explanation is clearly evident from an examination of the crystal structure of GaN. However, a general empirical explanation based on the incorporation probability of Ga can be developed from these results.

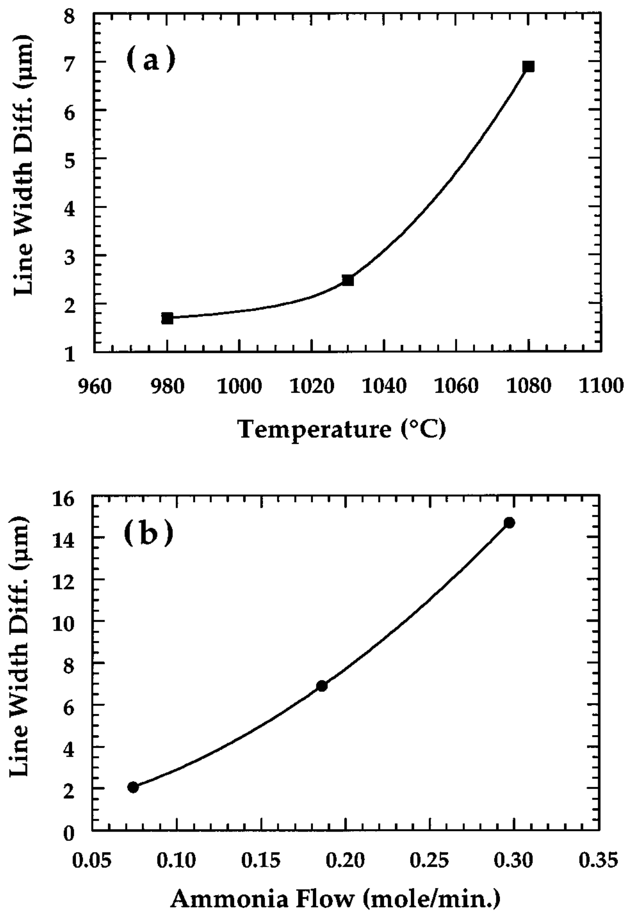

FIG. 3. Plots of linewidth difference as a function of regrowth temperature (a) and ammonia flow (b).

For growth on both pyramid sidewalls and line edges, the incorporation probability of TMGa is strongly affected by the group V partial pressure. The effective group III source flux at the line edge is enhanced due to the presence of the adjacent mask. Additionally, the effective group V reactor partial pressure is some fraction of the ammonia partial pressure due to the kinetic barriers to ammonia decomposition into active nitrogen. Lateral growth rate increases can be achieved by increasing the total ammonia partial pressure or by increasing the growth temperature, and thus the decomposition efficiency of the ammonia. In both cases the result is an increase in the surface active nitrogen concentration which in turn increases the incorporation probability of TMGa, and thus the lateral growth.

At very low ammonia flows, lateral growth in all directions essentially ceases, while vertical growth proceeds. This self-limiting characteristic was utilized for the first demonstration of electron field-emission devices based on GaN.[14] Investigations are currently underway to determine the mechanisms responsible for the stability of the $(1\bar{1}01)$ planes. A greater understanding of the origin of this phenomenon will not only assist in greater control of GaN selective epitaxy for a variety of applications, but will also promote an understanding of GaN planar growth, especially during the early stages of growth following the nucleation layer.

To summarize, highly anisotropic growth of GaN by selective epitaxy using linear mask patterns has been reported. Vertical and lateral growth rates have opposite orientation-related minima and maxima, with hexagonal symmetry. The lateral growth rate anisotropy is a strong function of growth parameters, with maximum anisotropy, and thus maximum epitaxial lateral mask overgrowth, obtained at high temperature and ammonia flow. Under optimized conditions, lateral to vertical growth rate ratios of up to 4.1 have been achieved.

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