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Effects of surface migration on InGaN/GaN multiple quantum wells selectively grown on periodic stripe openings separated by large SiO_2 covered spacing on Si (111) substrates

Xiaobiao Han[a], Hui Luo[a], Hang Yang[a], Jie Chen[a], Changming Zhong[a], Jiezhi Liang[a], Jieying Xing[a], Zhisheng Wu[a,b], Yang Liu[a,b,*], Baijun Zhang[a,b,*]

[a] School of Electronics and Information Technology, Sun Yat-sen University, 510006 Guangzhou, China
[b] State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, 510275 Guangzhou, China

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ABSTRACT

InGaN/GaN multiple quantum wells (MQWs) were selectively grown on patterned GaN/AlN/Si (111) templates with periodic stripe openings separated by large SiO_2 covered spacing. In comparison with the conventional epitaxial lateral overgrowth, the migration behaviours of group-III adatoms on the large mask region has a distinct effect on the structural and optical properties of InGaN/GaN MQWs selectively grown on the narrow stripe openings. In order to control them, a wide stripe window nearby the narrow one was adopted to modulate the local growth environments in our experiment. Flat and faceted InGaN/GaN MQWs stripes with trapezoidal cross section composed of basal (0001) plane and two semipolar $\{11\bar{2}2\}$ facets were obtained. The optical properties were investigated by the microscopic photoluminescence (micro-PL) measurement. The difference in emission peak positions observed by scanning the excitation laser across the stripes is related to the surface migration behaviour of the group-III adatoms on the SiO_2 masks.

1. Introduction

GaN-based laser diodes (LDs) are promising coherent light source in the green, blue and violet short wavelength region. Epitaxial lateral overgrowth (ELO), based on selective area growth (SAG), of III-nitrides is a main technique to obtain high-quality epitaxial layers for laser diode fabrication [1–3]. It is believed that SAG and ELO can reduce threading dislocations (TDs) density by blocking the dislocation propagation from the under layer using the oxide mask and bending the propagation of dislocations from the openings through facet control [4,5]. Blue and green LDs fabricated on ELO free-standing (FS) GaN layer on sapphire substrates had been realized with a long lifetime at room temperature due to the low dislocation density [6,7]. Compared with the very expensive FS-GaN, the cost effectiveness of GaN-based LDs can be greatly improved by using Si substrates. And, GaN grown on Si (111) exhibits an epitaxial relationship of GaN $[11\bar{2}0]$ // Si $[1\bar{1}0]$ [8], that is in favor of forming cleaved mirror facets for a Fabry-Perot (F-P) cavity LDs. Sun et al. [9] had already reported the first GaN-based blue–violet LDs directly grown on Si, which is operated under a continuous-wave (cw) current injection at room temperature. Due to the relatively high TDs density (~$6\times10^8 cm^2$), the operation lifetime was estimated to be about one minute, measured at 180 mA under cw injection. As mentioned above, SAG technique can reduce the TDs dramatically by 2–3 orders [5], and the lifetime will get a great improvement. There had been several reports on the optical pumped InGaN-based stripe LDs on Si substrates by SAG [10–12]. The stripe openings were oriented parallel to the GaN $[1\bar{1}00]$ axis, which allowed the mirrors to be formed by Si wafer cleavage. However, the period of stripe openings they used was only about 10 μm, which is not suitable for fabricating electrically driven F-P cavity LDs for the lack of enough interspace for single chip separation as well as electrodes fabrication.

There is seldom reports on the SAG on narrow stripe openings separated by large spacing up to now, and the growth process is very challenging. Previous reports had been demonstrated that many growth parameters such as the reactor pressure [13], growth temperature [14], stripe orientation [15–17], and fill factors (ratio of open width to pattern period) [18] can affect the surface morphology of re-grown GaN. Another key factor is the mass transport mechanism. There are two major mass transport processes: vapor-phase diffusion and surface diffusion, either on the masks or on the semiconductors. However, since the early studies were almost focused on the dense array of narrow stripes or dot openings with a small period, the surface migration

* Corresponding authors at: School of Electronics and Information Technology, Sun Yat-sen University, 510006 Guangzhou, China.
E-mail addresses: liuy69@mail.sysu.edu.cn (Y. Liu), zhbaij@mail.sysu.edu.cn (B. Zhang).

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behaviour of group-III adatoms on the masks was seldom investigated.

In this work, firstly, the n-GaN epitaxial layer was grown on periodic narrow-stripe openings with large SiO_2 covered spacing. By introducing a wide-stripe opening nearby the narrow one, the flat and faceted GaN stripes were obtained. It was believed that the morphology of re-grown GaN stripes is very sensitive to the local growth environments. Then, the InGaN/GaN MQWs were grown on the well-defined n-GaN stripes. It was found that the emitting wavelength of MQWs is dependent on the different facet. We proposed that the surface migration behaviour of group-III adatoms on the masks plays an important role on the optical properties of SAG InGaN/GaN MQWs.

2. Experimental details

The GaN/AlN template was firstly grown on a 2 in. diameter Si (111) substrate by MOCVD using trimethylgallium (TMG), trimethylaluminum (TMA) and NH_3 as precursors for Ga, Al, and N, respectively. The template consists of a 40 nm high-temperature AlN nucleation layer, two 400 nm GaN buffer layers, two 30 nm AlN interlayers, and a 1 µm GaN layer. Then, 100 nm SiO_2 was deposited by Plasma enhanced chemical vapor deposition and patterned with periodic stripe openings. There are two types of patterned templates for SAG (Fig. 1). One is periodic 5 µm narrow-stripe openings with a period of 300 µm (denoted as type-A pattern) along GaN $[1\bar{1}00]$ axis. The other one is also periodic 5 µm narrow-stripe openings with a period of 300 µm, but an additional 20 µm wide-stripe opening was induced at one side of the 5 µm narrow-stripe opening (denoted as type-B pattern). The distance between the narrow-stripe opening and the wide one was 15 µm. After careful cleaning by degreaser and acid, the patterned templates were reloaded into the MOCVD chamber to grow n-GaN. The regrowth temperature and reactor pressure of n-GaN structure were 1095 °C and 100 mbar, respectively. H_2 was used as the carrier gas. Then, InGaN/GaN MQWs structure were selectively grown on type-B patterned template. The growth reactor pressure of MQWs growth was 200 mbar, and the growth temperature of InGaN well and GaN barrier were 800 °C and 850 °C, respectively. The carrier gas was changed to N_2. The MQWs were terminated with a ~20 nm thin GaN cap layer.

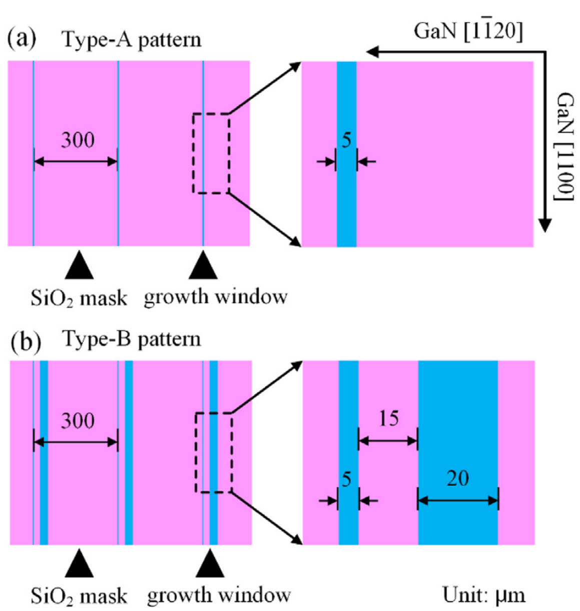

Fig. 1. Schematic diagram of (a) Type-A pattern, (b) Type-B pattern for SAG.

The structural properties were characterized by scanning electron microscopy (SEM, Hitachi S-4300) and scanning transmission electron microscope (STEM, FEI Tecnai Osiris with extreme-FEG). The specimen for STEM was prepared by dual beam focussed beam (FIB) milling (FEI Helio Nanolab). The optical properties were characterized by confocal micro-PL at room temperature (RT) (LabRAM HR 800). Both excitation and collection of PL were through a microscope objective lens, and the PL property of each growth facet could be investigated separately. He-Cd laser was used as the excitation source, of which the wavelength and excitation power were 325 nm and 5 mW, respectively.

3. Results and discussion

Fig. 2(a) shows the top view SEM images of the three samples with the growth conditions are summarized in Table 1. Roughly, all the samples have similar shape with no obvious particles on the masks, indicating a good selectivity. However, observed from the zoom-in pictures, the c-plane of sample 1 shows a rough surface with many pits, while it becomes much flatter for sample 2. This discrepancy is more obvious in the corresponding cross section SEM images in Fig. 2(b). Sample 1 shows an obvious "hump-like" cross section shape, indicating that a higher growth rate at the edge than the centre region, and the slope semipolar planes are continuously curved (not faceted). While, sample 2 shows a flat and faceted trapezoidal shape composed of a basal (0001) plane bounded by two slope $\{11\bar{2}2\}$ facets. It was noting that the widths of lateral overgrowth were measured as 9.5 µm for both sidewalls of sample 1. Likewise, the widths of lateral overgrowth were measured as 2.25 and 2.78 µm for the left- and right-side of the 5 µm narrow-stripe of sample 2, respectively. By reducing the growth time, the volume of sample 3 is comparable with sample 2 with the lateral expansion was around 2.6 µm. However, it still presents a "hump-like" shape and a rough surface with many pits. The different performance in the morphology between sample 1 and sample 3 may be ascribed to the different pattern designs between type-A and type-B.

There are two additional source supply paths for SAG [19]: migration from masked region (MMR) and lateral vapor-phase diffusion (LVD). Fig. 3 illustrate the group-III source materials supply processes of: (a) ELO GaN, (b) SAG GaN with type-A pattern and (c) SAG GaN with type-B pattern, respectively. In the case of ELO GaN (Fig. 3(a)), both MMR and LVD effects are weak due to the densely-arrayed narrow stripes. With increasing the space of opening windows (Fig. 3(b)), both MMR and LVD effects will enhance the local growth rate remarkably. As well known, the LVD effect is due to the lateral concentration gradient of the precursors. In comparison with type-A, the widths of openings in type-B are larger. The LVD effect will be stronger to some extent. But we know that the vapor diffusivity of precursors is very high, and the widths of openings in type-A and B are still narrow, leading to almost same concentration of precursors in the vapor phase. Thus the LVD effect could be neglected. The discrepancy in the lateral expansion of 5 µm narrow-stripe of the two type patterns is mainly determined by MMR effect. Rozhavskaya et al. [20] reported that the diffusion length of Ga adatoms on the top surface of GaN is larger than 20 µm under the typical growth conditions. In type-B pattern, a part of the Ga adatoms absorbed on the mask could migrate from the left side of 5 µm narrow-stripe to other side and even further to the 20 µm wide-stripe opening. While the Ga adatoms migrated from the right side of the 5 µm narrow-stripe are mainly consumed on the 20 µm wide-stripe opening. For the case of type-A pattern, the Ga adatoms absorbed on the masks migrate to the 5 µm narrow-stripe from the two sides, leading to a very high local growth rate for both lateral and vertical directions. As the results shown in Fig. 2(b), the lateral expansion of 5 µm narrow-stripe of type-