High-performance III-nitride blue LEDs grown and fabricated on patterned Si substrates

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Abstract

InGaN/GaN based blue LEDs with 2-μm-thick crack-free GaN buffer layers were successfully grown and fabricated on patterned Si (111) substrates. The patterns on the substrates include 340 μm × 340 μm square islands, separated by 3-μm deep and 20 μm wide trenches, along the (110) and (112) crystalline orientations. In addition to using the patterned growth technique, thin AlN and SiNx interlayers grown at high temperatures were also employed to partially release the residual stress and to further improve the crystalline quality. Blue LEDs of 300 × 300 μm² fabricated on the islands, without thinning and packaging, exhibited a high output power of around 0.7 mW at a drive current of 20 mA. Compared to III-nitride LEDs grown on sapphire substrates, the same LED structures grown on patterned Si substrates showed a few nm of red shift in emitting wavelength, suggesting some residual stress of GaN on patterned Si.

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1. Introduction

The realization of solid-state lighting mainly depends on the improvement of LED efficiency and lowering of manufacturing cost. One way to lower the manufacturing cost of light-emitting compounds is to utilize advanced Si-based technology as much as possible. However, it is more challenging to grow device-quality GaN films on Si substrates as compared with sapphire and SiC substrates due to the large mismatch in the lattice constants and the thermal expansion coefficients between GaN and Si. In particular, the 56% difference in thermal expansion coefficients usually results in significant cracking even in 1-μm-thick GaN films grown on Si (111) substrates, during cooling from high growth temperatures to room temperature [1,2]. Furthermore, curvature of the grown wafers caused by the large tensile stress of the GaN films is unfavorable and problematic to subsequent device fabrication.

Optical loss of the absorbing Si substrate is another disadvantage for realizing high brightness LEDs compared to those on transparent sapphire or SiC substrates. However, successful development of nitride-based LEDs on Si substrates will allow for much lower manufacturing cost (grown on 6- to 12-in Si substrates) and simplicity for the low- and mid-end blue, green, and white LED markets. Recently, our group has developed a novel approach combining the growth of high-quality GaN on patterned silicon and wet etching technology to shape the GaN [3]. Using this technique and wafer bonding technology, it is feasible to transfer the III-nitride LED structures from the large size Si substrates to other transparent or high thermal conductivity substrates. This will greatly enhance the performance of the LEDs, leading to low-cost and high-performance devices.

Many techniques have been attempted to improve the crystalline quality of GaN epilayers grown on Si substrates and to eliminate cracks [4–6]. Over the past few years, some progress has been made in nitride-based materials and LED devices on Si substrates [7,8]. More than 2-μm-thick crack-free GaN epilayers grown on Si substrates have been
obtained using various methods. Furthermore, III-nitride LEDs grown on Si substrate with output power ranging from several µW to nearly 1 mW packaged devices were reported recently [9–13].

Other complex techniques of creating better substrates for GaN on Si growth such as ex-situ deposition of AlAs and SiC will bring additional costs to have LEDs on Si substrates. It may even beat the original purpose of cost advantage for LEDs on Si compared with those on other substrates. Simple methods with high manufacturability are the most desirable. We believe the patterned Si substrate technique is ideal for LED structures growth because the single-step patterning process can be performed easily before growth and may help with the layer transfer afterward.

In this work, we employed patterned Si substrates to grow III-nitrides to release the tensile stress of GaN epilayers. Low temperature (LT) grown multiple AlN interlayers were usually adopted to achieve crack-free thick nitride-based layers. However the quality of the epilayers may be influenced to some extent because recrystallization of the LT-AlN is difficult to control when the temperature is raised. We believe high temperature (HT) grown AlN interlayers are more effective in improving the quality of the epilayers and the tensile stress can also be released more efficiently. In this study, 2 µm crack-free n-GaN layers and LEDs were grown on the patterned silicon substrate, assisted with HT-AlN nucleation layer, SiNx, and HT-AlN interlayer.

2. Experimental procedures

Square islands 340 µm × 340 µm in size, separated by 3-µm deep and 20-µm wide trenches, along the \(\{1\ 1\ 0\}\) and \(\{1\ 1\ 2\}\) crystalline orientations, were patterned by an STS ICP-RIE Si deep etch system on 2-in Si substrates. Conventional InGaN/GaN based LED structures were grown by metal–organic chemical vapor deposition (MOCVD) in an Aixtron 2000HT system. TMG, TMAl, TMIn and ammonia were used as precursors for Ga, Al, In and N, respectively. TEGa was used as the source for InGaN quantum wells growth instead of TMG. SiH4 and CP3Mg were used as n-type and p-type doping sources. Prior to growth, the substrates were heated up to 1170 °C for 10 min under an H2 ambient to remove the native oxide on the surfaces of Si substrates. In each growth run, both patterned and unpatterned (1 1 1) Si were used. The same LED structures were also grown on sapphire substrates for comparison. The LED structures consisted of a thin nucleation layer, a 2-µm-thick Si-doped GaN layer, five periods InGaN/GaN MQWs with a well thickness of 2.4 nm and a barrier thickness of 10 nm, a 20-nm-thick Mg-doped p-AlGaN layer and a 150-nm-thick Mg-doped p-GaN layer. The difference between the LED structures on sapphire substrate and on Si substrates is that the former used a LT GaN as nucleation layer and the latter used HT AlN layer instead of the LT-GaN layer, followed by a SiNx layer. To further reduce the tensile stress, an additional 10 nm HT-AlN interlayer was inserted in the middle of the n-GaN layer. The AlN nucleation layer, SiNx layer and n-GaN layer were all grown at 1150 °C, while the AlN interlayer was grown at 950 °C. The InGaN/GaN MQWs and the p-type layers including p-AlGaN and p-GaN were grown at 780 and 1030 °C, respectively.

Before growing complete LED device structures, we investigated the effects of the SiNx and HT-AlN interlayers by growing additional test samples with detailed results described below. Two back to back runs of 1 µm GaN, with and without the SiNx interlayer after the AlN nucleation layer, were grown for material analysis and comparison. Two other growth experiments of 1 µm GaN, one with LT-AlN interlayer and another with HT-AlN interlayer were grown on unpatterned Si substrates for comparison also.

LED chips of 300 µm × 300 µm were fabricated on the islands correspondingly. During the process, the p-type layer was selectively etched to expose the n-type layer using an ICP etching system. Ni/Au (5 nm/5 nm) transparent metal was evaporated as the p-type contact by e-beam evaporation and annealed in a rapid thermal annealing system at 500 °C for 5 min in a N2:H2 = 4:1 mixing gas. Ti/Al (30 nm/150 nm) metal was used as n-type ohmic contact. Ti/Au metal with thickness of 50 nm/150 nm was followed to achieve both p- and n-contact pads.

Double crystal X-ray diffraction (XRD) measurements were performed with \( \lambda = 0.15406 \) nm. Photoluminescence (PL) measurements of the samples were carried out using the 325 nm line of a He–Cd laser as the excitation source with 30 mW output power. The thicknesses of GaN epilayers and AlN layers were estimated in-situ from the “Filmetrics” reflectometry using a beamed light source at 600 nm. The light output power of the LED was measured using the integrated sphere detector.

3. Results and discussion

AlN was used as the nucleation layer for initiation of GaN growth on Si (1 1 1) substrates. The purpose of the AlN nucleation is to decrease the mismatch dislocations, to compensate the tensile stress, and to control the intrinsic stress by coalescence of islands during the nucleation. LT-AlN and HT-AlN nucleation layers were adopted by a few groups [14,15]. Apparently no obvious difference was found between them. HT-AlN nucleation layer was used in our experiment, with a growth temperature of 1150 °C. A SiNx layer was deposited on the top subsequently at the same temperature. The reduction of tensile stress in the growing layers using an in-situ SiNx mask was attributed to an increase of grain size in the lateral growth over the masked area [16,17]. Lower density of dislocation was found in the epilayer because of the lateral growth and the effect of dislocation termination [18,19]. High resolution X-ray diffraction (HRXRD) ω-scans were employed to evaluate the crystal quality of GaN grown, as shown in Table 1. The sample with SiNx interlayer shows a
significant decrease in the FWHM of the (1 0 2) diffraction, compared with the sample without the SiN$_x$ layer. The FWHM of the (0 0 2) is only sensitive to the density of screw threading dislocation, while the FWHM of (1 0 2) includes the information of all threading dislocations. The XRD data show that the SiN$_x$ interlayer not only decreased the tensile stress but also blocked the spreading of the edge and mixed dislocations. The thickness of the SiN$_x$ interlayer is a critical parameter to determine the crystalline quality. Too thick SiN$_x$ interlayer will influence the coalescence of GaN buffer layer while too thin of the SiN$_x$ interlayer has less effect on the stress release and quality improvement of the epilayer.

Amano et al. [20] demonstrated that LT-AlN interlayer (500°C) can eliminate cracks of AlGaN grown on sapphire substrates. The LT-AlN interlayer also lowered the threading dislocation density, improved the crystalline quality and reduced tensile stress generated during the subsequent HT GaN growth. The degree of tensile stress reduction is related to the AlN interlayer growth temperature. However, the quality of subsequent HT-GaN may not be improved effectively when the LT-AlN interlayers recrystallize at HT. Furthermore, extra time is needed for temperature ramp down and ramp up. It is worthwhile trying to grow the AlN interlayer in a HT condition, which can save the growth time and make the process more controllable. Higher temperature growth can not only improve the quality of GaN epilayer but also have better control of the tensile stress. A temperature of 960°C was adopted in our experiment after optimization. A comparison of HRXRD ϕ-scans for 1μm GaN samples with LT- and HT-AlN interlayers are shown in Table 2. The FWHM of (0 0 2) diffraction is almost the same, while the FWHM of (1 0 2) diffraction of the samples with HT-AlN is narrower than those with LT-AlN. We concluded that HT AlN interlayer can serve as a dislocations filter, especially for the edge and mixed dislocations.

After the growth parameter optimization, 2μm crack-free n-GaN layers with mirror like surface were obtained (Fig. 1(a)). During the LED fabrication, heat treatment such as activation of p-doping at 950°C and annealing of p-contact at 500°C were performed on the samples. No cracks were observed on the surface of the LED structure after the process (Fig. 1(b)). Although GaN was also deposited on the trench areas, clear gaps can be observed between the islands and the trenches in cross-sectional pictures, resulting from the difference in height of the grown layers, as shown in Fig. 2(a). Fig. 2(b) shows that the cracking lines in the trench areas were terminated at the interface between the platform and the trench. As a result, the tensile stress caused by the mismatch of thermal expansion coefficients between the epilayer and substrate can be released efficiently. Due to the large ratio in the width of the islands and trenches, there is little edge effect of the resulting growth. Fig. 3 shows a comparison of the room temperature PL spectra of two GaN on Si samples

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Comparison of the FWHM of (0 0 2) and (1 0 2) diffractions for the samples with and without SiN$_x$ layer (the thickness of GaN epilayer is 1.0μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN sample</td>
<td>FWHM (0 0 2) (arcsec)</td>
</tr>
<tr>
<td>With SiN$_x$ layer</td>
<td>522</td>
</tr>
<tr>
<td>Without SiN$_x$ layer</td>
<td>520</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Comparison of the FWHM of (0 0 2) and (1 0 2) diffractions for the samples with LT-AlN and HT-AlN interlayer (the thickness of GaN epilayer is 1.0μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN sample</td>
<td>FWHM (0 0 2) (arcsec)</td>
</tr>
<tr>
<td>With LT-AlN layer</td>
<td>564</td>
</tr>
<tr>
<td>With HT-AlN layer</td>
<td>582</td>
</tr>
</tbody>
</table>
grown in the same run, with and without patterns. The patterned sample exhibits stronger PL intensity compared to the unpatterned sample. The result can be attributed to improvement of the crystalline quality of the epilayer with lower tensile stress or compressive strain [21].

The same LED structures were grown on patterned silicon and sapphire substrates. The LED structures were characterized by HRXRD $\omega$–$2\theta$ scan, as shown in Fig. 4. Compared with the sample grown on the sapphire substrate, the period of the quantum wells in the sample on silicon substrate was somewhat different. Based on simulation results, the period changed from 12.4 to 13.0 nm. The In composition in MQW was almost the same.

300 $\mu$m x 300 $\mu$m LED chips were fabricated on these samples. The L-I characteristics of the two unpackaged LED samples are shown in Fig. 5. An output power of around 0.7 mW at 20 mA drive current can be achieved for the LED grown on Si substrates, while the LED grown on
sapphire substrates shows an output power of 2.46 mW at the same drive current. This power performance is about double of that in the most recent report [12]. The L-I curve of the LED grown on Si substrate drops suddenly at 120 mA, while the curve of the LED on sapphire substrate shows a sub-linearity until 200 mA. Although the Si substrate is better in thermal dispersion, the poor light extraction efficiency of the absorbing Si substrate degrades the L-I performance significantly, compared with the transparent sapphire substrate. Furthermore, higher turn-on voltages, as shown in Table 3, were measured on LEDs on Si, namely, higher voltages were applied on these diode at the same drive current. Lower Si-doping concentration was found in the sample on Si substrates, as determined by C–V measurements, leading to higher resistances and forward voltages. Fig. 6 shows the room temperature electroluminescence (EL) spectra of the LEDs. LEDs grown on Si substrate emit at a wavelength about 15 nm longer than that on sapphire substrates, even though the same In composition was incorporated in the MQWs. The reason for the red shift can be attributed to the residual tensile strain in the LEDs, which was also confirmed by a slight curvature of the wafer.

For the LED grown on Si substrate, lower output power compared with that on sapphire results from several reasons. Firstly, light absorption by the silicon substrate is a major loss of the output power. Secondly, the quality of GaN on Si still has plenty of room for improvement, compared with that on sapphire. Thirdly, the LED structural design and growth parameters need further optimization since the change of period for the MQW structure was found by HRXRD measurement. Therefore, solving the above three aspect, will improve the performance of the LED on silicon substrate further.

4. Conclusion

In summary, crack-free InGaN/GaN based blue LEDs were successfully grown and fabricated on square islands patterns. The use of the SiNx and HT-AlN interlayers improved the quality of the epitaxial layer and released the tensile stress. The LEDs grown on the Si substrates exhibited an output power of 0.7 mW at 20 mA drive current, which we believe is one of the best results reported. The wavelength was red shift compared with the LED on sapphire substrates using the same MQW growth conditions.

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References


Table 3
Comparison of the characteristics between the LEDs on Si and on sapphire sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Output power (mW)</th>
<th>Wavelength (nm)</th>
<th>FWHM (nm)</th>
<th>Vth (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED on patterned Si</td>
<td>0.70</td>
<td>453</td>
<td>21.8</td>
<td>4.3</td>
</tr>
<tr>
<td>LED on sapphire</td>
<td>2.46</td>
<td>438</td>
<td>19.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Fig. 6. EL spectra of the LEDs on Si and sapphire substrates.