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Effect of Graded $Al_xGa_{1-x}N$ Layers on the Properties of GaN Grown on Patterned Si Substrates

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2.2-μm-thick crack-free GaN films were grown on patterned Si substrates. The crack-free GaN films were obtained by patterning Si substrate and optimizing the graded $Al_xGa_{1-x}N$ layers. With the increase of the graded $Al_xGa_{1-x}N$ layer thickness, the GaN crystal quality improved as judged from the X-ray diffraction data. By applying multi-$Al_xGa_{1-x}N$ layers on the patterned Si substrate, a 31% reduction of tensile stress for the GaN film was obtained as measured by micro-Raman. For the AlGaN/GaN high electron mobility transistor grown on 1 x 1 cm^2 larger patterns, the device exhibits maximum drain current density of 776 mA/mm and maximum transconductance of 101 mS/mm.

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have been studied extensively for high power transistors applications in recent years.[1–3] Many reports have demonstrated fabricated devices made from GaN-based materials with very high breakdown voltages, this is very significant especially for applications such as inverters for next-generation electric vehicles.[4–7] High breakdown is an essential characteristic for these types of power electronics and GaN-based devices have been shown to be the promising candidates for such applications.

The common substrate choices for the AlGaN/GaN HEMTs are sapphire, SiC and Si. Among these substrates, Si is the only one to offer large wafer size with proper power dissipation capability and low cost. The epitaxial growth of GaN on Si for high power application has been reported, for example, Selvaraj *et al.* reported high breakdown voltage AlGaN/GaN HEMTs on Si through the use of thick GaN buffer.[8] However, the fact that cracks occurred in the GaN films during cooling down process limits the use of Si substrates for GaN power device applications.

There are many reports about the growth of crack-free GaN films on Si substrate by using various buffer layer structures such as AlN,[9–12] AlGaN,[13,14] superlattice structure,[15,16] AlN interlayers[17–21] and SiN interlayers[22–24] to relieve the stress level; however, the growth of thicker GaN film on Si without cracks is still challenging.

Several studies on crack-free GaN film on Si have demonstrated the benefits of using patterned Si substrates to reduce the thermal stress. Zamir *et al.* demonstrated lateral confined epitaxy (LCE) method and grew 0.7-μm-thick crack-free GaN on 14 × 14 μm^2 square Si patterns.[25] Wang *et al.* used LCE method to grow 1-μm-thick GaN on patterned Si substrates with 100 × 100 μm^2 windows.[26] Zhang *et al.* obtained 2-μm-thick GaN on patterned Si substrates with 340 × 340 μm^2 windows.[27] Krost and Dadgar *et al.* reported selective area growth (SAG) of GaN on Si substrate with 100 × 100 μm^2 patterned areas.[28] Chen *et al.* grew 2-μm-thick GaN on 300 × 300 μm^2 patterned Si substrates.[29] A similar approach using patterned Si substrates has been demonstrated for the fabrication of AlGaN/GaN HEMT devices for RF applications.[30] However, for practical device fabrication on patterned GaN films, it is necessary to grow GaN film with thickness more than 2 μm and with patterned areas larger than 300 × 300 μm^2. Up to now, it is still a challenge to grow the GaN film on patterned Si substrate due to large tensile stress induced in the large dimension patterns.

In this work, the GaN films were grown on patterned Si substrates with 300 × 300 μm^2 windows. In order to further reduce the stress in the film and eliminate the cracks, several graded $Al_xGa_{1-x}N$ buffer layers with different compositions were grown and compared. Crack-free films with thickness more than 2 μm were obtained. AlGaN/GaN HEMT device with high current density was achieved on 1 × 1 cm^2 patterns with the proper choice of multi-$Al_xGa_{1-x}N$ buffer layers.

2. Experimental Procedure

To define the window areas, 300 nm Si_xN_y film was first deposited on 2-in. Si wafers by plasma-enhanced chemical vapor deposition (PECVD). 300 × 300 μm^2 windows in the nitride layer were formed by photolithography and reactive ion etching (RIE) processes. After windows were formed, the wafers were loaded into the EMCORE D-180 metal–organic chemical vapor deposition (MOCVD) system for the epitaxial growth, both patterned Si wafers and unpatterned Si wafers were loaded for direct comparison.

A buffer layer was grown before the growth of GaN films to reduce the stress of the GaN films. The buffer layer usually consisted of multi-AlN layers (high temperature-AlN/low temperature-AlN/high temperature AlN) and multi-$Al_xGa_{1-x}N$ layers (high-Al composition $Al_{0.38}Ga_{0.62}N$/graded $Al_xGa_{1-x}N$/low-Al composition $Al_{0.13}Ga_{0.87}N$). Both multi-AlN buffer layers and multi-$Al_xGa_{1-x}N$ layers were also used to improve GaN film quality and to release the stress. The total thickness of the multi-$Al_xGa_{1-x}N$ layers including the graded $Al_xGa_{1-x}N$ layers were varied for comparison.

Detailed layer structures are shown in Fig. 1. Structures A–C represent 1-μm-thick GaN grown on multi-$Al_xGa_{1-x}N$

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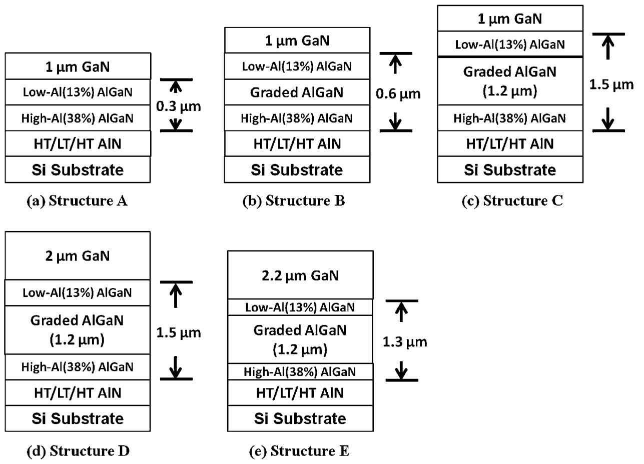

Fig. 1. Different epitaxial structures of GaN on Si substrates.

layers with different thicknesses. Structure D represents 2-μm-thick GaN on multi-$Al_xGa_{1-x}N$ layers with 1.5 μm $Al_xGa_{1-x}N$ layers same as structure C. Structure E represents 2.2-μm-thick GaN grown with 1.3-μm-thick multi-$Al_xGa_{1-x}N$ layers. The samples were characterized by optical microscopy (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD) and micro-Raman measurement.

35-nm-thick $Al_{0.23}Ga_{0.77}N$ was grown on structure E with pattern windows of $1 \times 1\,cm^2$. The AlGaN/GaN HEMT devices have a source–drain distance of 7 μm, a source–gate distance of 1.5 μm, a gate–drain distance of 4.5 μm, a gate length of 1 μm and a total gate width of 100 μm.

3. Results and Discussion

Figure 2 shows the OM images of GaN films grown on different multi-$Al_xGa_{1-x}N$ layers buffer structures. Samples A_{un} and A in Fig. 2(a) are from samples with buffer structure A of Fig. 1(a). Here the subscript "un" represents unpatterned substrate. There was no graded $Al_xGa_{1-x}N$ layer in this buffer layer and the Al ratios in the two $Al_xGa_{1-x}N$ films were fixed at 13 and 38%. These 1-μm-thick GaN films grown on both unpatterned Si and patterned Si substrates show serious cracks.

Figures 2(b)–2(d) show the GaN layers on buffer structures which include a graded $Al_xGa_{1-x}N$ layer, as represented by samples B_{un}, B, C_{un}, C, D_{un}, and D. Again the subscript "un" represents unpatterned substrate. As shown in Figs. 2(b) and 2(a), the crack densities of samples B_{un} and B are less than that of samples A_{un} and A. Again, in Figs. 2(b) and 2(c), the crack density decreases as the thickness of the graded $Al_xGa_{1-x}N$ layer increases, from less than 0.6 to 1.2 μm. On samples with 1.2-μm-thick graded $Al_xGa_{1-x}N$ layer, patterning of Si substrate shows a very strong effect. A very obvious difference can be observed on the surfaces of samples C_{un} and C. A crack-free GaN film structure was achieved on the patterned Si wafer, but under the same growth condition with similar graded $Al_xGa_{1-x}N$ buffer layer, the crack-free GaN film cannot be obtained on unpatterned Si substrate. With further increase of the GaN thickness to 2 μm, severe cracks were observed on sample with unpatterned Si, but no crack was found on the sample with patterned Si, as shown in samples D_{un} and D of Fig. 2(d).

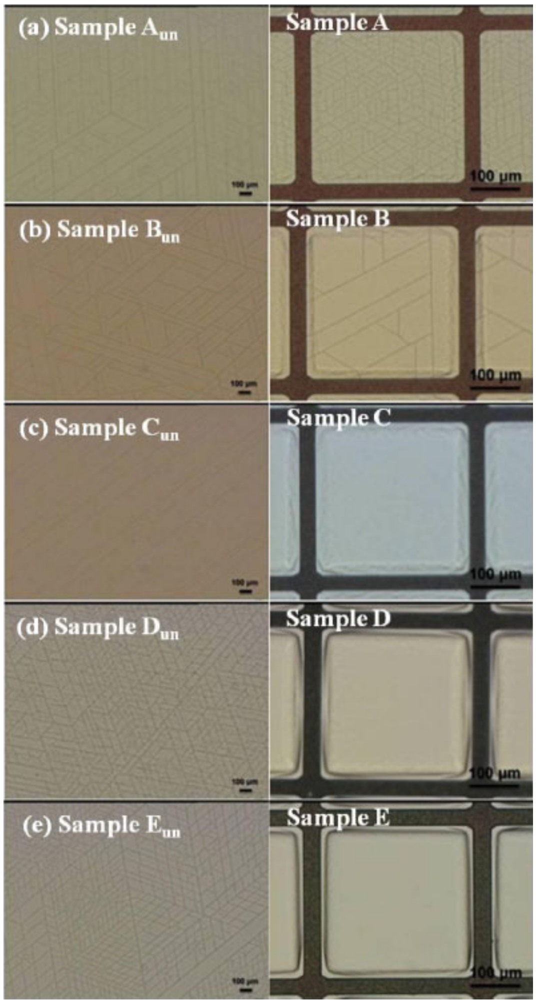

Fig. 2. (Color online) OM images of GaN surfaces. Crack-free GaN can be observed on samples C, D, and E.

Cracks formed due to the thermal mismatch between the GaN layer and the Si substrate. The use of a graded $Al_xGa_{1-x}N$ layer effectively reduces this stress. However, as the GaN thickness increases, the use of graded $Al_xGa_{1-x}N$ layer alone is no longer sufficient to reduce the stress in this thicker film. In this case, the use of patterned Si shows clear advantage.

High resolution X-ray diffraction data for all the samples were taken. The FWHMs of X-ray diffraction data of GaN (002) peaks from samples with different buffer structures are shown in Fig. 3. For 1-μm-thick GaN (samples A, A_{un}, B, B_{un}, C, and C_{un}) in Fig. 1, the crystalline quality of GaN improves with the graded $Al_xGa_{1-x}N$ layer thickness for both the patterned and unpatterned substrate cases. For GaN grown on unpatterned Si substrates with the GaN thickness less than 1 μm, the crystalline quality can be improved and the crack density can be reduced by using a buffer layer consists of multi-$Al_xGa_{1-x}N$ layers, as in the cases of samples A_{un}, B_{un}, and C_{un}. When the GaN thickness on unpatterned Si was increased to 2 μm, the material showed severe cracks, as shown in sample D_{un}, as this happens, there is a reduction of FWHMs for the GaN (002) peak. In the case of 2-μm-thick GaN grown on patterned Si substrates (samples D and E), there was no crack formation on the GaN film and the crystalline quality was further improved.

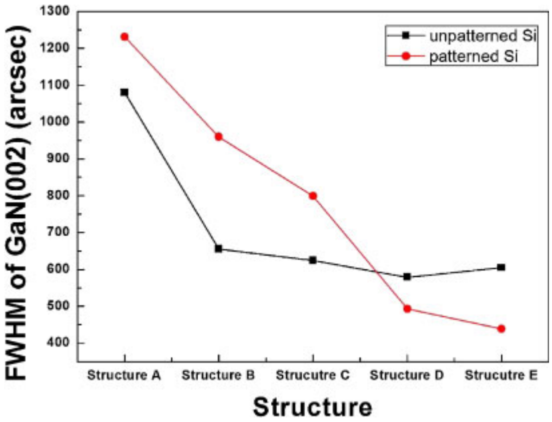

Fig. 3. (Color online) FWHMs of XRD rocking curves for GaN (002) on unpatterned Si samples (circle) and patterned Si samples (square).

Thicker GaN film on patterned Si substrate, such as in sample E with 2.2-μm-thick GaN, can be achieved by adjusting the thickness of the multi-$Al_xGa_{1-x}N$ layers. The FWHM of GaN (002) peak in the sample E is only 438.7 arcsec, which is narrower than GaN film grown on the unpatterned Si substrate.

The cross-sectional SEM image of the epitaxial layers on the patterned Si substrate (sample E) is shown in Fig. 4(a), where 2.2-μm-thick GaN was successfully grown on 2-in. patterned Si substrate. The top view SEM images of GaN film grown in the $300 \times 300\,\mu m^2$ windows, which show crack-free surfaces, are given in Figs. 4(b) and 4(c).

From these results, it can be seen that it is possible to grow crack-free thick GaN film Si substrate by using patterned Si substrate with proper choice of multi-$Al_xGa_{1-x}N$ layers. It is shown that both the substrate patterning and the use of multi-$Al_xGa_{1-x}N$ layers help the stress relaxation. The degree of relaxation can be determined by stress measurement of the GaN film using micro-Raman technique. The tensile stress here is calculated from the Raman shift of the GaN E_2 peak. The results of stress distributions of different samples are shown in Fig. 5. The micro-Raman measurements were performed in seven positions across the $300 \times 300\,\mu m^2$ GaN window area, as shown in the inserted picture in Fig. 5. In samples B–E, the tensile stress distribution shows a plateau in the center and gradual reductions toward the edges of the window. Wang *et al.* reported similar stress relaxation phenomenon on free surfaces of patterned structure.[26] Different from other samples which show a typical reduction of stress near sample edges, in sample A the stress remains almost constant throughout the sample, this is because severe cracks near the edge release the stress in the sample.

Among the five samples, sample E with 2.2-μm-thick GaN shows lowest tensile stress, which is less than that of sample D by 0.28–0.32 GPa. For these two samples, only the thicknesses of the $Al_xGa_{1-x}N$ layers are different. A significant improvement can be obtained by adjusting the thicknesses of the high-Al content $Al_xGa_{1-x}N$ layer and the low-Al content $Al_xGa_{1-x}N$ layer. In the case of the buffer structure of sample E, an impressive 31% reduction in tensile stress was obtained. Therefore, the stress can be effectively reduced by adjusting the multi-$Al_xGa_{1-x}N$ layer

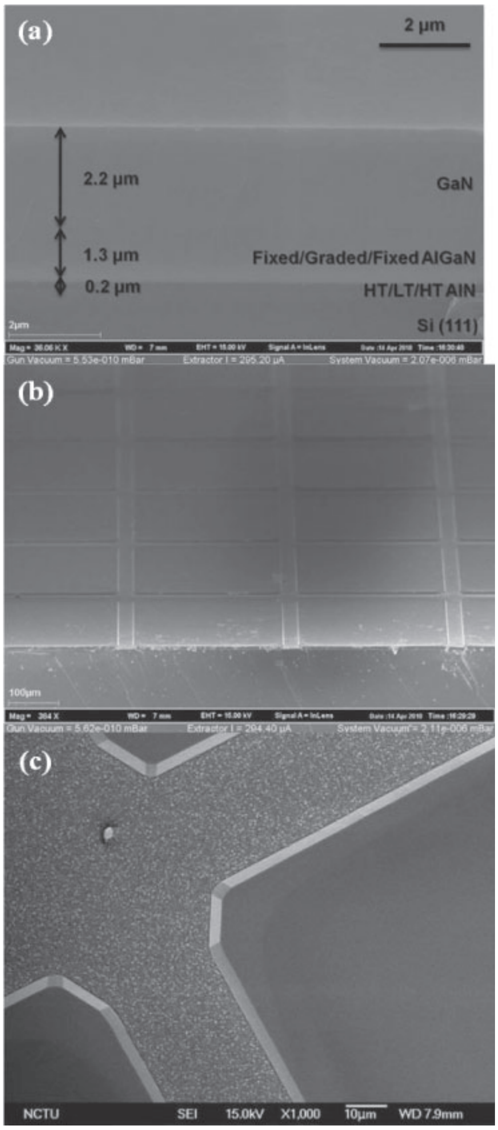

Fig. 4. (a) Cross-sectional SEM image of sample E on the patterned Si substrate. (b) Top view SEM image of an array of GaN grown on $300 \times 300\,\mu m^2$ patterned Si substrate. (c) Top view SEM image of crack-free GaN surface.

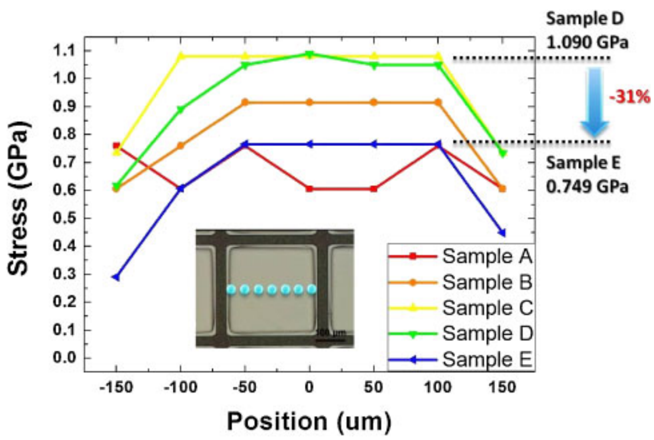

Fig. 5. (Color online) Stress distributions of GaN grown on patterned Si substrates. Stresses are calculated by Raman shift.

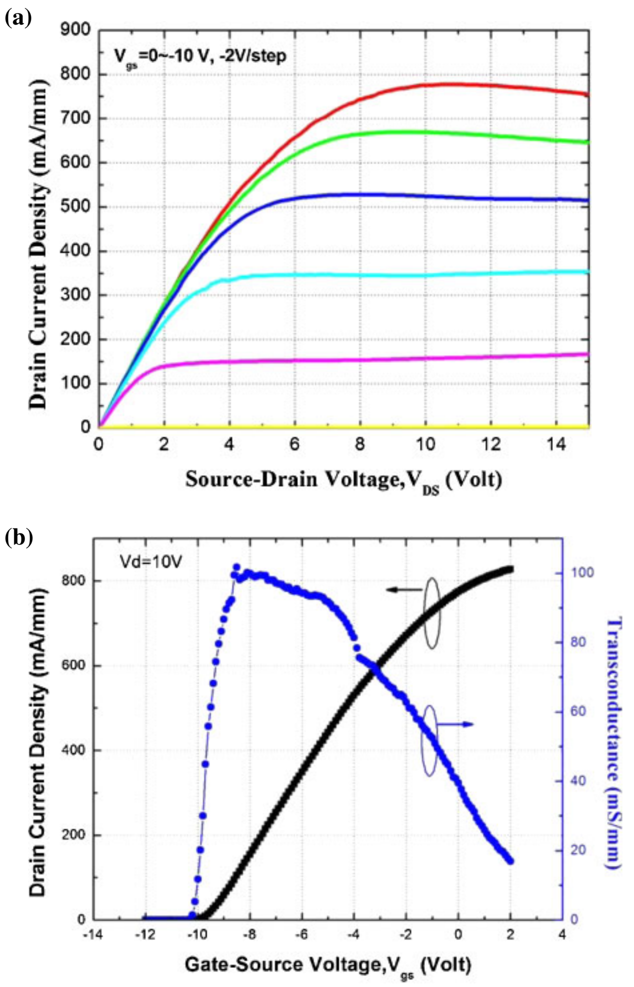

Fig. 6. (Color online) (a) *I*–*V* characteristic of HEMT on patterned Si. (b) Transfer characteristics of HEMT on patterned Si.

buffer structure and the crack formation can thus be prevented.

Structure E was also grown on the Si substrate with larger patterns with the window size of $1 \times 1\,cm^2$. AlGaN barrier layer was grown on the top of the template to form the heterostructure. The device characteristics of HEMT grown on patterned Si substrate are shown in Figs. 6(a) and 6(b). The device exhibits maximum drain current density of 776 mA/mm and maximum transconductance of 101 mS/mm. These results are comparable to the performance of the best GaN HEMT grown on Si substrate. Furthermore, the breakdown voltage of the fabricated device is higher than 150 V. It also demonstrates the potential of applying this method for future power electronic applications.

4. Conclusions

In this study, crack-free 2.2-μm-thick GaN layer was successfully grown on patterned Si substrates by MOCVD. This GaN layer showed much better crystalline quality than similar film grown on unpatterned substrate. Using well-adjusted multi-$Al_xGa_{1-x}N$ layers in the patterned structure, a 31% reduction in tensile stress was obtained. Moreover, the high quality crack-free thick GaN HEMT structure grown by combining the patterned Si substrate with multi-$Al_xGa_{1-x}N$ layers buffer can also be confirmed by DC performances.

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