Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp971-972

Reuse process of sapphire substrates for GaN epitaxial growth using laser lift-off technique

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Abstract

We tried to develop reuse process of sapphire substrates for gallium nitride (GaN) epitaxial growth, and we succeeded in removing GaN-based high electron mobility transistor (HEMT) epitaxial heterostructure from a sapphire substrate using a short-pulse laser, and regrowing the same heterostructure onto the reused sapphire substrate by MOCVD. We found that there was no significant difference in crystal quality or electrical properties by comparing the removed GaN-HEMT epilayer and the regrown one. These results indicated that we could reuse sapphire substrates for GaN growth and also develop the reuse process of sapphire substrates using the laser lift-off technique.

1. Introduction

GaN-based transistors are the most promising electron devices not only for high-power and high-voltage applications but also for millimeter- and terahertz-wave wireless communication ones; this is because GaN-based HEMTs can demonstrate higher maximum oscillation frequency (f_{max}) and current-gain cutoff frequency (f_T). In fact, f_{max} close to 600 GHz and f_T over 450 GHz were ever reported [1-3]. These high performances were mainly due to optimization of epitaxial structure, self-aligned gate, and regrowth techniques.

For usage of higher frequencies such as unused millimeter- and terahertz-wave bands (30 GHz to 3 THz), we have fabricated $In_{0.18}Al_{0.82}N/AlN/GaN$ HEMTs on sapphire, SiC, Si and free-standing GaN substrates and investigated the effect of InAlN barrier thickness on device performance for improving their f_T and f_{max} [4-7]. In our recent works, we reported an f_{max} of 287 GHz for the 45-nm-gate MES-HEMT on the free-standing GaN substrate with 3-nm-thick InAlN barrier layer [6].

To apply GaN-HEMTs to millimeter- and terahertz-wave MMICs, it is necessary to thin the substrate to less than 100 μm. However, sapphire and SiC substrates need to be thinned by dry etching or mechanical polishing because they are resistant to acid and/or alkali solutions, which means most of the substrate material is discarded. In this study, we tried to reuse sapphire substrates for GaN epitaxial growth and develop reuse process of sapphire substrates using a laser lift-off technique.

2. Laser lift-off process of GaN epilayer

We first grew an $In_{0.18}Al_{0.82}N/AlN/GaN$-HEMT epitaxial heterostructure on a 3-inch sapphire substrate by MOCVD. Table I shows the $In_{0.18}Al_{0.82}N/AlN/GaN$-HEMT structure, which was almost the same as one for fabricating nanoscale GaN-HEMTs ever reported [4].

Table I GaN-HEMT epitaxial heterostructure grown by MOCVD.

Layer	Thickness (nm)
i-$In_{0.18}Al_{0.82}N$	9
i-AlN	0.8
i-GaN	2000
Nucleation layer	
3-inch sapphire substrate	

We used a DISCO DFL7560L, a laser lift-off system with a solid-state laser, to remove the GaN-HEMT epitaxial heterostructure from the sapphire substrate. The DISCO DFL7560L is primarily used for peeling off sapphire substrates from blue LED crystal layers of GaN compound materials. Figure 1 shows the laser lift-off process to remove the GaN epitaxial heterostructure from the 3-inch sapphire substrate using the DFL7560L. The removing of the GaN epilayer was carried out by irradiating a short-pulse laser from the rear surface of the sapphire substrate, whereby only GaN was thermally decomposed into metallic Ga and N_2 gas [8]. The wavelength, power and pulse frequency of the short-pulse laser were adjusted so as to be absorbed into only GaN.

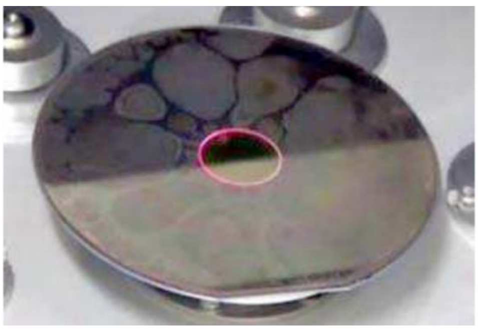

Fig. 1 Laser lift-off process to remove GaN-based epitaxial heterostructure from a sapphire substrate. Bubbles are N_2 gas formed by thermally decomposition of GaN crystal using a short-pulse laser.

After the lift-off process and separation of the GaN epilayer, Ga metal was left on the front surface of the sapphire substrate. We then cleaned the whole sapphire substrate by using HCl solution for GaN regrowth. As shown in Fig. 2, we could etch and remove the Ga completely. Furthermore, there was no damage on the surface of the sapphire substrate judging from microscopic and AFM observations.

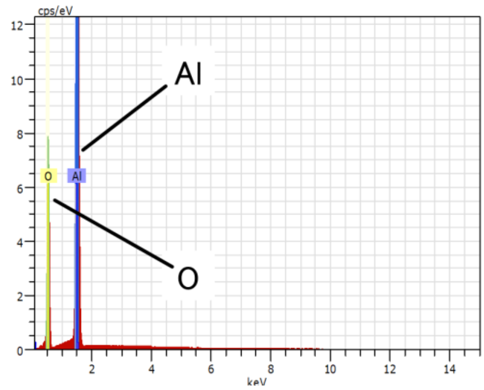

Fig. 2 EDX spectra of the sapphire surface after cleaning by using HCl solution.

3. GaN regrowth onto reused sapphire substrate

Next, we grew the epilayer, which was the same as the removed GaN-HEMT heterostructure, onto the reused sapphire substrate by MOCVD. The growth condition was almost the same as the first growth one. Figure 3 shows a photograph of the GaN-HEMT wafer regrown on the reused 3-inch sapphire substrate.

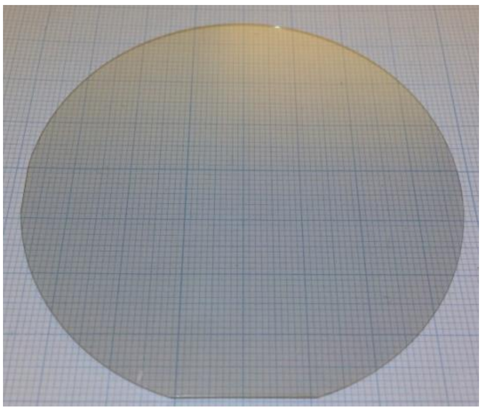

Fig. 3 Photograph of a GaN-HEMT wafer regrown on the reused 3-inch sapphire substrate.

We measured and evaluated crystal quality and electrical properties of the removed and regrown GaN epilayers by XRD, AFM and Hall effect measurement systems, and found that there was no significant difference among them as shown in Table II. These results indicated that we could reuse sapphire substrates for GaN epitaxial growth using the laser lift-off technique, and that we succeeded in developing the reuse process of sapphire substrates for GaN epitaxial growth by using the DISCO DFL7560L and its short-pulse laser lift-off procedure.

Table II Crystal quality and electrical properties of removed GaN-HEMT epitaxial heterostructure and regrown one on reused sapphire substrate.

Evaluation items	Removed GaN epi.	Regrown GaN epi.
InAlN barrier thickness	9.9 nm	9.3 nm
Al content of InAlN barrier	0.830	0.820
(0002) XRD-FWHM	561.6 arcsec	378.0 arcsec
(10-12) XRD-FWHM	561.6 arcsec	788.4 arcsec
Sheet resistance	327.4 Ω/sq.	358.5 Ω/sq.
Variation of sheet resistance	±2.8%	±6.4%
RMS of surface roughness (1×1 μm^2)	0.468 nm	0.486 nm
RMS of surface roughness (5×5 μm^2)	0.614 nm	0.777 nm

4. Conclusions

We developed reuse process of sapphire substrates for GaN epitaxial growth, and we succeeded in removing GaN-HEMT epitaxial heterostructure from the sapphire substrate using the short-pulse laser, and regrowing the same heterostructure onto the reused sapphire substrate by MOCVD. There was no significant difference between removed and regrown GaN-HEMT epilayers in crystal quality or electrical properties, indicating that we could reuse sapphire substrates for GaN epitaxial growth and also develop the reuse process of sapphire substrates using the short-pulse laser lift-off technique.

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