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SAW characteristics of GaN layers with surfaces exposed by dry etching

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Abstract: We evaluated the possibility of monolithic integration of electron devices and surface acoustic wave (SAW) devices on GaN. We removed top n+ GaN layers of n+ GaN/unintentionally-doped GaN structures by inductively coupled plasma (ICP) etching and fabricated SAW filters on the exposed unintentionally doped GaN layers. We found that the device characteristics are almost the same as those of devices fabricated on as-grown GaN layers, although the surface morphology of GaN layers is degraded due to the ICP etching. The results indicate that SAW devices and electron devices can be monolithically integrated on GaN-based semiconductor structures.

Keywords: GaN, sapphire, surface acoustic wave, SAW, HEMT, monolithic integration
Classification: New functional devices and materials

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1 Introduction

Because of their excellent electrical and thermal properties, GaN-based electron devices, such as AlGaN/GaN high electron mobility transistors (HEMTs,) have been widely investigated for high-frequency and high-power applications [1, 2]. GaN-based surface acoustic wave (SAW) devices have also been explored due to the large piezoelectricity of GaN [3]: The properties of GaN-based SAW filters, such as SAW velocity dispersion [4], temperature dependence [5], responce to ultraviolet illumination [6], and side-gate effects [7] have been previously reported.

One of the features of GaN SAW devices is their potential for monolithic integration with AlGaN/GaN HEMTs. Such integration would likely be achieved by locally dry-etching the top AlGaN layers of AlGaN/GaN heterostructures and fabricating SAW devices on the exposed GaN surfaces.

In this letter, as the first step for integrating SAW and electron devices, we examine the properties of SAW devices on GaN layers exposed by dry etching.

2 Sample growth and characterization

We grew 0.1-μm-thick heavily-Si-doped GaN/2-μm-thick unintentionally–doped high-resistive GaN structures by metal organic chemical vapor deposition (MOCVD) on (0001) sapphire substrates (sample A). The doping concentration in the n$^+$-GaN layer was nominally $1 \times 10^{19}\,\mathrm{cm}^{-3}$. We also prepared 2-$\mu$m-thick unintentionally doped GaN layers on sapphire substrates (sample B). We characterized the samples using X-ray diffraction (XRD) methods and found that the full widths at half maximum of (0002) XRD rocking curves of both samples were 360 arcsec. We then observed the as-grown sample surfaces with an atomic force microscope (AFM). After this AFM observation, the Si-doped GaN layer of sample A was locally removed by Cl$_2$-based inductively coupled plasma (ICP) etching and the exposed unintentionally doped GaN layer was observed with the AFM. Images of 5.0 μm by 5.0 μm areas of the as-grown surfaces are shown in Figs. 1 (a) and (b). Atomic step structures are observed, and the average surface roughness (Ra) values of the two surfaces are commonly as small as 0.2 μm. These results demonstrate the excellent morphology of the as-grown surfaces. Such atomic step structures, however, are not observed in the exposed GaN layer [Fig. 1 (c)]. Furthermore, the Ra of the GaN surface exposed by the ICP

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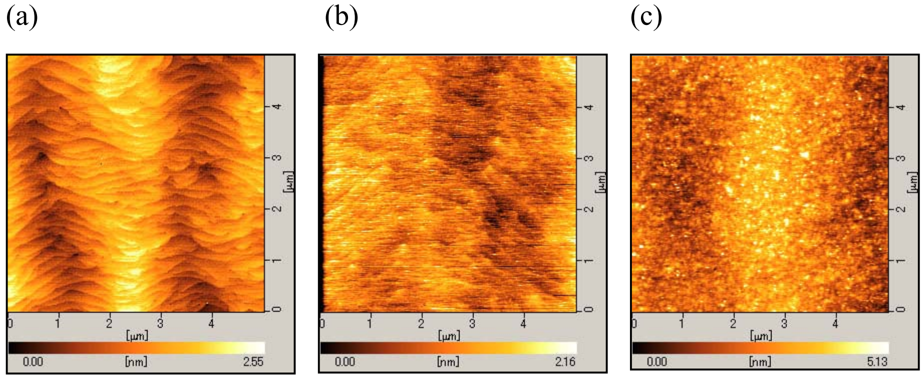

Fig. 1. AFM image.
(a) As-grown sample surfaces of the Si-doped GaN layer. (b) As-grown sample surfaces of unintentionally doped GaN layers. (c) The surface of exposed unintentionally doped GaN layer after etching Si-doped GaN layer.

etching is 0.5 μm. The surface morphology of sample A is, consequently, likely to be degraded due to the ICP etching.

3 SAW device fabrication and performance

We fabricated SAW filters with SAW wavelength of 8 μm on sample A and sample B. The IDTs were formed by Al evaporation and lift-off using an i-line stepper. Their line and space are commonly 2 μm. The SAW filters are composed of 50 pairs of 100-nm-thick Al-based interdigital transducers (IDTs). Two IDTs in a single SAW filter are separated by 5 mm along the [01-10] direction of the sapphire substrates. The IDT aperture lengths are 800 μm.

We measured the S-parameters between 540 and 640 MHz at the input power of 10 dBm. The RF characteristics (magnitude of S21) of the two filters at room temperature are shown in Fig. 2. Shark peaks are clearly observed for both filters. The positions and heights of the peaks are, respectively, 580 MHz and −28.2 dB for the device on sample A, and 581 MHz and −26.6 dB for the one on sample B. We also observed clear side lobes in both characteristics, which implies that those signals are contributions from SAWs propagating in the GaN layer. Noting that dispersion in SAW velocities appears in GaN-on-sapphire systems [4], the separation between the two main peaks is likely to be due to the difference in GaN-layer thickness in the two samples. More importantly, the peak for the device on sample A is lower than the peak for the device on sample B by 1.6 dB.

We also measured the RF characteristics of the filters at room temperature (25°C) and 200°C. The ambient temperature was controlled using employed equipment. Results for the device on sample A and B are shown in Figs. 3 (a) and (b), respectively. The side lobes are not marked in the respective figures, which is likely due to some parasitic effects from the employed equipment. Frequencies for the main peaks decreased by approxi-

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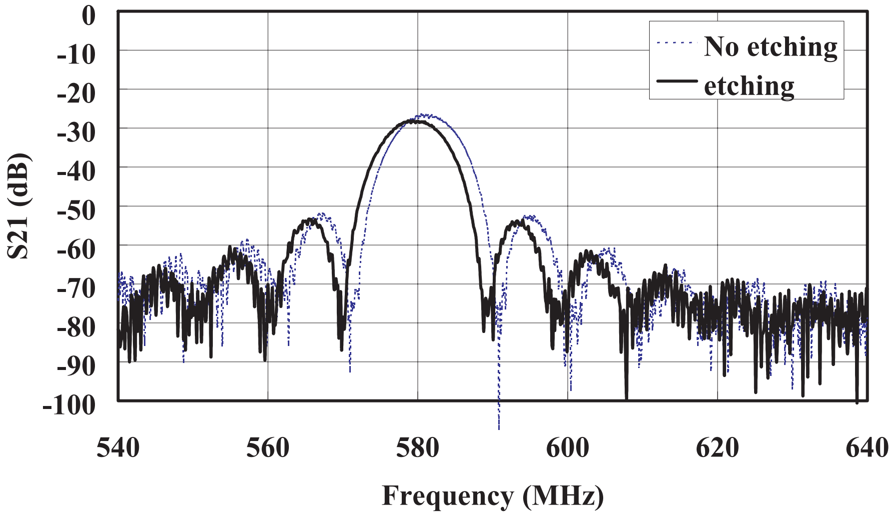

Fig. 2. RF characteristics of the two filters at room temperature.

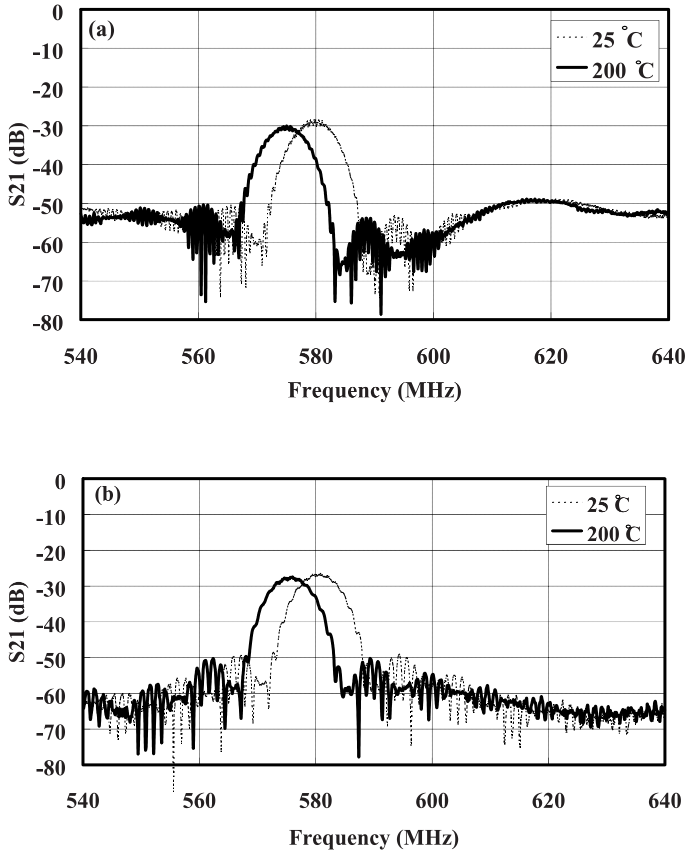

Fig. 3. RF characteristics of the filters at room temperature (25°C) and at 200°C. (a) The filter fabricated after n^+-GaN etching. (b) The filter fabricated without etching.

mately 5 MHz for the respective devices when the ambient temperature is raised from 25 to 200°C. The change in the frequencies is consistent with the temperature coefficient of the frequency values [5]. Furthermore, the height

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of the main peak for the sample-A device decreased by 1.5 dB for the ambient temperature increase. A change of the same magnitude was also observed for the sample-B device.

The result that the difference in the main peak height between the two devices is as small as 1.5 dB at room temperature suggests that the ICP-etching-based surface morphology degradation in sample A, which is apparent in the AFM observation, does not seriously influence the SAW properties. There might be formed damages and deep levels on the exposed GaN surface through the ICP-etching process. A large number of damage-oriented carriers could degrade the SAW properties when the ambient temperature is raised. Such a hypothesis, however, quite unlikely because we observed no essential difference in the main-peak height changes between the two devices for the ambient temperature increase. The obtained results indicate that SAW properties in GaN layers with surfaces exposed by the ICP-etching process are essentially the same as those in as-grown GaN layers. This suggests that SAW devices fabricated on GaN layers achieved by etching off the top AlGaN layers in AlGaN/GaN heterostructures should operate normally and that GaN SAW devices should be able to be successfully integrated with AlGaN/GaN HEMTs.

4 Conclusion

We fabricated SAW filters on unintentionally-doped GaN layers with surfaces exposed by Cl_2-based ICP etching grown on (0001) sapphire substrates. The performance of the SAW filters was quite similar to that of filters fabricated on as-grown unintentionally doped GaN layers both at room temperature and at 200°C, although surface morphology was degraded by the etching process. The results indicate that the SAW properties are not seriously influenced by the surface morphology degradation caused by the ICP etching and suggest that SAW filters are likely to be successfully integrated with electron devices on AlGaN/GaN heterostructures.

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