Abstract—This study proposes GaN thin film as a piezoelectric material for SAW (surface acoustic wave) filters. Highly piezoelectric GaN film with a good surface morphology (RMS roughness $= 0.7 \text{ nm}$) was obtained on a $2\times 2$-in $(0001)$-oriented sapphire substrate by MOCVD growth. The fabricated GaN SAW filter exhibited a very high velocity of $5803 \text{ m/s}$ and relatively low insertion loss of $\sim 7.7 \text{ dB}$. The attenuation of the center frequency was about $22 \text{ dB}$ smaller than those at the tops of the first sidelobes. When the wavelength of the IDT electrode was $60 \mu\text{m}$ ($\lambda/4 = 15 \mu\text{m}$), the center frequency was measured at $96.6 \text{ MHz}$, thereby facilitating a $\sim \text{GHz}$ operation when the IDT geometry is designed on a $1 \mu\text{m}$ scale. The calculated electromechanical coupling factor ($K^2$) was about $4.3 \pm 0.3\%$, which is larger than those obtained from other thin film piezoelectric materials and allows the realization of wider filter fractional bandwidths. TCF (temperature coefficient of frequency) was measured as low as $\sim -18.3 \text{ ppm/}^\circ\text{C}$ in the range from $-25$ to $50 \text{ }^\circ\text{C}$. These superior characteristics demonstrate that epitaxially grown GaN thin film can be successfully used for high-performance SAW filters.

Index Terms—GaN, MOCVD, SAW filter, TCF.

I. INTRODUCTION

THE DEVELOPMENT of GHz-band surface acoustic wave (SAW) devices has become necessary because of the increased volume of information and communication media, such as portable telephones, mobile telephones, and satellite broadcasting. The various approaches for developing GHZ-band SAW devices include, the identification of new materials with high SAW velocities, the application of a submicron rule process to the fabrication of conventional SAW devices and/or taking advantage of harmonic waves or higher modes.

Thin-film piezoelectric materials have long been utilized in the field of microwave devices. The application of SAW devices, based on materials such as LiNbO$_3$, LiTaO$_3$, quartz, ZnO, and AlN has been developed since the mid-1970s [1]–[6]. The characteristics required for a microwave band material consist of a smooth surface and good temperature stability, along with a high phase velocity, large electromechanical coupling factor ($K^2$), and small transition loss.

III-nitride wide band gap materials, grown either in the [0001] direction of a wurtzite structure or in the [111] direction of a zinc-blend structure, exhibit strong lattice polarization effects, as both directions are parallel with the polar axes [7]. This suggests that III-nitride materials are uniquely suited for application in high temperature piezoelectronics, pyroelectric sensors [8], and SAW devices [9], [10]. AlN is a promising material for SAW devices because it has a high SAW velocity, which qualifies it for GHZ-band application. Devices working at over $2 \text{GHz}$ have already been built [11], [12]. However, until now, there have been no other reports on a SAW device fabricated on an epitaxially grown GaN thin film. This is because an undoped GaN epitaxial layer, even grown by very sophisticated MOCVD (metalorganic chemical vapor deposition) or MBE (molecular beam epitaxy), usually exhibits a high electrical conductivity, due to residual donors unintentionally introduced during the growth, which increases the insertion loss of the device that is fatal in realizing a good SAW device. Accordingly, to be used as a piezoelectric material for a SAW filter, the grown GaN thin film must include a high resistivity as well as a high bulk and surface crystallinity.

II. EXPERIMENTAL

All the GaN samples in this work were grown in a vertical type MOCVD system with a resistively heated rotating disk reactor. High purity hydrogen gas (H$_2$) was used as both the carrier gas and for the make-up flow to supplement the total flow rate required to maintain a well-matched laminar flow pattern within the reactor. The total gas pressure during the growth was set at 200 torr and the spinning rate of the substrate was about 1000 rpm. The substrate used for the epitaxial growth of the GaN thin films was a $(0001)$-oriented 2-in sapphire and the temperature of the substrate surface was monitored using an IR pyrometer. Trimethylgallium (TMGa), bis(cyclopentadienyl) magnesium(Cp$_2$Mg), dimethyl zinc(DMzn), and ammonia (NH$_3$) were used as the Ga, Mg, Zn, and N sources, respectively.

The key features of the GaN growth process were as follows.

1) Substrate was heated to $1020 \text{ }^\circ\text{C}$ in a stream of ambient H$_2$ for cleaning.

2) The substrate temperature was then lowered to $500 \text{ }^\circ\text{C}$ at a constant rate and a 360 Å-thick amorphous-like GaN layer was grown as a buffer layer between the sapphire substrate and the single crystalline GaN layer.

3) After the growth of the buffer layer, the substrate temperature was then re-elevated to $1020 \text{ }^\circ\text{C}$ for the growth of high quality Mg-doped GaN films with different thicknesses of 0.5, 1.3, and 2.0 $\mu\text{m}$.

The thickness of the undoped or Zn-doped GaN samples was fixed at $1.3 \mu\text{m}$. During the growth, the typical flow rates were maintained at 7.0 slpm for both NH$_3$ and H$_2$, 100 $\mu\text{mol/min}$ for TMGa, and 2.88 and 2 $\mu\text{mol/min}$ for Cp$_2$Mg and DMzn, respectively.

Manuscript received March 30, 2000; revised October 24, 2000. The review of this paper was arranged by Editor U. Mishra.

The authors are with the School of Electronic and Electrical Engineering, Kyungpook National University, Taegu 702-701 Korea (e-mail: jlee@ee.knu.ac.kr).

Publisher Item Identifier S 0018-9383(01)01463-0.
respectively. The resulting growth rate of all the samples was as high as about 2.1 \( \mu \text{m/hr} \).

The GaN SAW filters were composed of a normal interdigital transducer (IDT) with 18 pairs of single \( \lambda/4 \) electrodes with a \( \lambda \) of 10, 15, and 20 \( \mu \text{m} \), where \( \lambda \) was the wavelength of the SAW of the synchronism frequency. The dimensions and characteristics of the pattern for the SAW IDT are summarized in Table I. Al electrodes with a thickness of 200 nm were evaporated. The patterning of the electrodes for the SAW IDT was performed by a conventional lift-off process. A schematic diagram of the cross section and top picture of the IDT/GaN/sapphire SAW filter are shown in Fig. 1(a) and (b). The width and spacing of the IDT fingers were both 10, 15, and 20 \( \mu \text{m} \), which are considerably wider compared to those of the SAW device patterns fabricated by contemporary sophisticated lithography. The selection in design parameters, such as the same width and spacing of IDT finger (generally recognized as most basic design rule), wide line width, and relatively small finger numbers (18 periods), is not only for the simple device fabrication but also for the purpose of easily understanding the SAW characteristics for GaN piezoelectric thin film itself, because GaN thin film as a SAW filter has never been used.

The surface morphology and crystallinity of the GaN films were analyzed using AFM (atomic force microscopy: DI nanoscope) and synchrotron analysis. Finally, the frequency response of the SAW filters fabricated on the various GaN epitaxial layers was measured using a HP 8753D network analyzer.

### III. RESULTS AND DISCUSSION

#### A. Epitaxial Growth of Highly Resistive Piezoelectric GaN Thin Film

The growth of a GaN piezoelectric material with a good crystallinity and surface morphology is important, as these qualities have a strong affect on SAW’s when they propagate through the surface of a piezoelectric material from an input to an output IDT. However, the growth of a highly resistive piezoelectric GaN film is also crucial in order to maintain a good electrical isolation between the IDT electrodes and hence a small insertion loss.

Accordingly, three different types of epitaxial growth, undoped, Zn-doped, and Mg-doped GaN, were investigated in this work to determine which sample satisfies the requirements mentioned above. The surface RMS roughness was measured as 0.2, 0.6, and 0.9 nm for the undoped, Zn-doped, and Mg-doped GaN layers with a 1.3 \( \mu \text{m} \) thickness, which indicates that the undoped or Zn-doped GaN layer had a better surface morphology than the Mg-doped one. However, both the undoped and the Zn-doped GaN films exhibited lower sheet resistivity values, from \( 10^5 \) to \( 10^6 \) \( \Omega \text{cm} \), which are insufficient to guarantee a good SAW performance.

Generally, an Mg-doped GaN film exhibits semi-insulating properties caused by the formation of Mg–H complexes [13] when the samples are not post-annealed at a high temperature. In this study, the sheet resistivity of the Mg-doped GaN film was determined as higher than \( 10^7 \) \( \Omega \text{cm} \) using a four-point probe. Since the surface resistance of the input IDT of the SAW filter fabricated on this layer was measured as higher than \( 10^9 \) \( \Omega \), the Mg-doped GaN film was selected with the expectation that it would produce a better device performance, even though it has a little inferior surface morphology.

In addition, the thickness of the Mg-doped GaN layer was varied to identify its relative effect on the surface morphology. AFM images of the Mg-doped GaN films are shown in Fig. 2. When the GaN thickness was 0.5 \( \mu \text{m} \), the RMS roughness of the

![Fig. 1. Schematic diagram of cross-section (a) and top picture (b) of fabricated GaN SAW filter.](image-url)
measured surface was 2.5 nm. However, as the thickness was increased up to 2.0 \( \mu \text{m} \), the surface of the GaN film became smooth with an RMS roughness of 0.7 nm, which was close to the value of the 1.3 \( \mu \text{m} \)-thick undoped sample. A smooth surface morphology is essential for achieving the characteristics required for a microwave band material.

Fig. 3 shows the high-resolution synchrotron X-ray diffraction curve of the Mg-doped GaN films with different thicknesses. The crystallinity of the Mg-doped GaN film was also improved with an increased thickness. When the thickness was increased from 1.3 to 2.0 \( \mu \text{m} \), the full width at half maximum (FWHM) of the X-ray diffraction peaks was decreased from 475 to 460 arcsec, which is sufficiently narrow when considering that Mg-doping usually degrades the crystallinity of a GaN epitaxial layer. In contrast, 0.5 \( \mu \text{m} \)-thick Mg-doped GaN film exhibited poor crystallinity with a very wide FWHM of 840 arcsec (insert in Fig. 3).

The surface roughness and crystallinity were not further improved with increasing the thickness above 2 \( \mu \text{m} \). Meanwhile, the observed propagation velocity of SAW device on GaN/sapphire tended to be a little decreased as the thin film thickness was increased. The 1.3 and 2.0 \( \mu \text{m} \) thick epilayers were therefore chosen to fabricate the SAW devices, because both layers have a relatively good surface morphology and crystallinity and demonstrate relatively high propagation velocity.

B. Frequency Response of GaN SAW Filters

Due to the converse piezoelectric effect, an electrical RF signal applied to an IDT of a GaN SAW filter produces a mechanical stress in a GaN film. The result is a periodic mechanical displacement, which then travels as a Rayleigh-type wave along the surface of a GaN film. Fig. 4(a) and (b) show the respective frequency response of the SAW filters for the 1.3 \( \mu \text{m} \)-thick Zn-doped (\( \lambda = 40 \mu \text{m} \)) and undoped (\( \lambda = 80 \mu \text{m} \)) GaN film which had IDTs with 18 pairs of single electrodes at both the input and the output. From these figures, the wave propagation velocities on the Zn-doped and undoped GaN film were calculated to be 5425 and 5520 m/s at center frequencies of 135.628 MHz and 69.402 MHz, respectively, which are much higher than those of other materials such as LiNbO\(_3\), LiTaO\(_3\), and ZnO [14]–[16]. However, the insertion losses for both samples were about 50 dB, which is too large for use in practical SAW filters. These large insertion losses may be due to the lower sheet resistivity of the Zn-doped and undoped GaN film, as described above.

Fig. 5 shows the frequency response of the 2 \( \mu \text{m} \)-thick Mg-doped GaN SAW filter with an IDT with 18 pairs of single electrodes (\( \lambda = 00 \mu \text{m} \)). The peak at 96.687 MHz indicates the fundamental mode, and peaks at 291.413 and 486.605 MHz correspond to the harmonic modes. The frequency responses at the center frequency are shown in Fig. 6(a) and (b) for the two Mg-doped samples with different thicknesses of 1.3 \( \mu \text{m} \) and 2.0 \( \mu \text{m} \). In both samples, the attenuation of the center frequency near 96.725 MHz was 22 dB smaller than those at the tops of the first sidelobes. In spite of the absence of a suitable impedance matching, the insertion losses were as low as –9.87 dB and –7.74 dB for the 1.3 and 2.0 \( \mu \text{m} \) thicknesses, respectively, which would appear to be related to the inherently high sheet resistivity of Mg-doped GaN film. The value of –7.742 dB was smaller than that reported by Kaya et al. [17]
using AlN (14 dB) and Deger et al. [18] using AlGaN film (17 dB) as a piezoelectric material. A propagation velocity of 5803 m/s was obtained from the center frequency and wavelength ($\lambda = 60\ \mu m$), which is the highest value ever reported for a GaN-based SAW filter. Therefore, these superior characteristics would seemingly facilitate a GHz operation when the IDT geometry is designed using a 1 $\mu m$ scale. The frequency response characteristics of the various GaN SAW filters investigated in this work, are summarized in Table II. The Mg-doped GaN SAW filter with a high sheet resistivity exhibited a good frequency response with a low insertion loss and high propagation velocity.

The electromechanical coupling coefficient, $K^2$, was calculated using the crossed-field equivalent model [19] as in equation (1).

$$K^2 = G_a(f_0) / [8 \times f_0 \times C_T \times N] \quad (1)$$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mg-doped GaN</th>
<th>Zn-doped GaN</th>
<th>Undoped GaN</th>
</tr>
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<tbody>
<tr>
<td>Thickness ($\mu m$)</td>
<td>1.3</td>
<td>2.0</td>
<td>1.3</td>
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<tr>
<td>Wavelength ($\mu m$)</td>
<td>60</td>
<td>60</td>
<td>40</td>
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<tr>
<td>$\lambda/4$ line width ($\mu m$)</td>
<td>15</td>
<td>15</td>
<td>10</td>
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<tr>
<td>Center frequency (f, MHz)</td>
<td>96.768</td>
<td>96.725</td>
<td>138.40</td>
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<tr>
<td>Insertion Loss (dB)</td>
<td>-9.87</td>
<td>-7.74</td>
<td>-43</td>
</tr>
<tr>
<td>Propagation Velocity (m/s)</td>
<td>5806</td>
<td>5803</td>
<td>5425</td>
</tr>
<tr>
<td>3f$_0$ harmonic (MHz)</td>
<td>288.59</td>
<td>291.41</td>
<td>-</td>
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<tr>
<td>5f$_0$ harmonic (MHz)</td>
<td>488.34</td>
<td>486.605</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 4. Frequency response characteristics of fabricated GaN SAW filter with Zn doped GaN (a) and undoped GaN (b). The sample thicknesses were fixed at 1.3 $\mu m$.

Fig. 5. Frequency response characteristics of fabricated 2 $\mu m$-thick Mg-doped GaN SAW filter with wavelength of 60 $\mu m$.

Fig. 6. Frequency response characteristics of fabricated GaN SAW filter with wavelength of 60 $\mu m$ for two different thicknesses of Mg-doped GaN film (a) 1.3 $\mu m$ and (b) 2.0 $\mu m$.
Mg-doped GaN film can be successfully used for high performance SAW filters and facilitate a GHz operation when the IDT geometry is designed on a submicron scale.

IV. CONCLUSION

Mg, Zn-doped, and undoped GaN films were investigated for their potential SAW applications. An Mg-doped 2.0 µm-thick GaN film, fabricated on a 2-in (001)-orientated sapphire substrate by MOCVD, exhibited a sheet resistivity higher than 10$^7$ Ωcm along with a relatively good surface morphology (RMS roughness = 0.7 nm) and narrow high resolution synchrotron peak (FWHM = 400 arcsec).

With a wavelength of 60 µm, the fabricated Mg-doped GaN SAW filter exhibited a higher velocity and small insertion loss characteristics of 5803 m/s and −7.7 dB, respectively, at a 96.725 MHz center frequency without proper impedance matching. The attenuation of the center frequency was about 22 dB smaller than that at the tops of the first sidelobes. These superior frequency characteristics of the Mg-doped GaN SAW filter are seemingly related to its large electromechanical coupling factor ($K^2$) of 4.3 ± 0.3% and small TCF of −18.3 ppm/°C. Accordingly, it would appear that epitaxially grown Mg-doped GaN film is superior to other existing materials [14]–[16].

### References


### Table III

<table>
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<tr>
<th>Substrate</th>
<th>Propagation Velocity (m/s)</th>
<th>$K^2$</th>
<th>TCF (ppm/°C)</th>
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<tr>
<td>Quartz (ST-X)</td>
<td>3158</td>
<td>0.14</td>
<td>0</td>
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<tr>
<td>LiNbO$_3$ (128° Y-X)</td>
<td>3992</td>
<td>5.3</td>
<td>−75</td>
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<tr>
<td>LiNbO$_3$ (Y-Z)</td>
<td>3488</td>
<td>4.5</td>
<td>−94</td>
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<tr>
<td>LiTaO$_3$ (X-112° Y)</td>
<td>3288</td>
<td>0.6</td>
<td>−18</td>
</tr>
<tr>
<td>LiTaO$_3$ (Y-Z)</td>
<td>3254</td>
<td>0.72</td>
<td>−35</td>
</tr>
<tr>
<td>AlN film (C-axis)</td>
<td>4800</td>
<td>0.15-0.8</td>
<td>−26</td>
</tr>
<tr>
<td>ZnO film (C-axis)</td>
<td>2600</td>
<td>0.6-1.9</td>
<td>−25</td>
</tr>
<tr>
<td>Mg-doped GaN film (C-axis)</td>
<td>5806*</td>
<td>4.3*</td>
<td>−18.3*</td>
</tr>
</tbody>
</table>

where $G_{\text{a}}(f_0)$ radiation conductance at the center frequency $f_0$; $C_T$ static capacitance (total IDT capacitance); $N$ number of input IDT finger pairs.

The calculated $K^2$ was about 4.3 ± 0.3% for the 2 µm-thick GaN film, which is higher than other piezoelectric materials, except for LiNbO$_3$(40° Y − X, 60° Y − X). This suggests that epitaxially grown piezoelectric GaN thin film can easily realize wider filter fractional bandwidths. TCF of −18.3 ppm/°C was measured for the SAW filter on 1.3 µm thick Mg-doped GaN in the range from −25 to 50 °C, which is much lower than the values obtained from other SAW materials (except quartz). The values of propagation velocity, $K^2$, and TCF for GaN SAW filter were summarized in Table III and they were compared to those obtained from other SAW materials, indicating that the GaN SAW material is superior to other existing materials [14]–[16].

Suk-Hun Lee was born in Cheju, Korea, in 1969. He received the B.S. degree in electronic engineering from Cheju National University, Cheju, in 1995, and the M.S. and Ph.D. degrees in electronic engineering from Kyungpook National University (KNU), Taegu, in 1997 and 2000, respectively. He is currently pursuing the Ph.D. degree at KNU in the field of gallium nitride growth by MOCVD. His current research area is the growth of III-nitride based semiconductor and fabrication of GaN-based electronic devices.
Hwan-Hee Jeong was born in Ulsan, Korea, in 1973. He received the B.S. degree in electronic engineering from Kyungpook National University, Taegu, in 1999. He is currently pursing the M.S. degree at Kyungpook National University in the field of surface acoustic wave (SAW) device fabrication using gallium nitride grown by MOCVD.

His current research area involves microwave solid-state circuits and applications.

Sung-Bum Bae was born in Taegu, Korea, in 1974. He received the B.S. and M.S. degrees in electronic engineering from Kyungpook National University, Taegu, in 1997 and 1999, respectively. He is currently pursing the Ph.D. degree at KNU in the field of indium gallium nitride growth by MOCVD.

His current research area is the growth of III-nitride based semiconductor and fabrication of GaN-based electronic devices.

Hyun-Chul Choi was born in Taegu, Korea, in 1960. He received the B.S. degree in electronic engineering form Kyungpook National University (KNU), Taegu, in 1982, and the M.S. and Ph.D. degree in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1984 and 1989, respectively. His doctoral research concerned electromagnetic wave propagation and inverse scattering.

From 1989 to 1990, he was with Daehyun Precision, Taegu. Since 1990, he has been Associate Professor at the School of Electronic and Electrical Engineering, KNU. His current work involves rf and microwave devices and computational electromagnetics.

Jung-Hee Lee (M’97) was born in Taegu, Korea, in 1957. He received the B.S. and M.S. degrees in electronic engineering from Kyungpook National University (KNU), Taegu, in 1979 and 1983, respectively, the M.S. degree in electrical and computer engineering from Florida Institute of Technology, Melbourne, in 1986, and the Ph.D. degree in electrical and computer engineering from North Carolina State University, Raleigh, in 1990. His doctoral research concerned carrier collection and laser properties in monolayer-thick quantum well heterostructures.

From 1990 to 1993, he was with the Electronics and Telecommunication Research Institute (ETRI), Taechn, Korea, where he worked in the compound semiconductor research group. Since 1997, he has been an Associate Professor in the School of Electronic and Electrical Engineering, KNU. His current work is focused on gallium nitride-based electronic devices, atomic layer epitaxy, and vacuum microelectronics.

Yong-Hyun Lee (M’93) received the B.S. and M.S. degrees in electronic engineering from Kyungpook National University (KNU), Taegu, Korea, in 1975 and 1977, respectively, and the Ph.D. degree in electronic engineering from Choongnam National University, Korea, in 1991.

Since 1979, he has been with KNU and is a Professor in the School of Electronic and Electric Engineering. His current research interests include advanced device fabrication technology, novel device structures and materials, thin film transistors, microwave devices, and display technologies.

Dr. Lee is a member of the IEEE Electron Devices Society.