Quantification of Trace-Level Silicon Doping in Al\textsubscript{x}Ga\textsubscript{1-x}N Films Using Wavelength-Dispersive X-Ray Microanalysis

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Abstract

Wavelength-dispersive X-ray (WDX) spectroscopy was used to measure silicon atom concentrations in the range 35–100 ppm (corresponding to (3–9) \times 10^{19} \text{ cm}^{-3}) in doped Al\textsubscript{x}Ga\textsubscript{1-x}N films using an electron probe microanalyser also equipped with a cathodoluminescence (CL) spectrometer. Doping with Si is the usual way to produce the n-type conducting layers that are critical in GaN- and Al\textsubscript{x}Ga\textsubscript{1-x}N-based devices such as LEDs and laser diodes. Previously, we have shown excellent agreement for Mg dopant concentrations in p-GaN measured by WDX with values from the more widely used technique of secondary ion mass spectrometry (SIMS). However, a discrepancy between these methods has been reported when quantifying the n-type dopant, silicon. We identify the cause of discrepancy as inherent sample contamination and propose a way to correct this using a calibration relation. This new approach, using a method combining data derived from SIMS measurements on both GaN and Al\textsubscript{x}Ga\textsubscript{1-x}N samples, provides the means to measure the Si content in these samples with account taken of variations in the ZAF corrections. This method presents a cost-effective and time-saving way to measure the Si doping and can also benefit from simultaneous measuring other signals, such as CL and electron channeling contrast imaging.

Key words: electron probe microanalysis, secondary ion mass spectrometry, semiconductor analysis, silicon doping, trace-element analysis

Introduction

Wide band-gap semiconductors, such as Al\textsubscript{x}Ga\textsubscript{1-x}N and GaN, are used in a wide range of technologically important optical and electrical devices, including high brightness LEDs, high electron mobility transistors (HEMTs) and laser diodes (Roccarelli et al., 2018; Tsao et al., 2018). Controlled doping of these alloys is crucial for control of the electronic properties of the epitaxial layers and hence optimal device performance. Si and Mg are typically employed as the n- and p-type dopants, respectively, in both Al\textsubscript{x}Ga\textsubscript{1-x}N and GaN (Van de Walle et al., 1999).

Optoelectronic devices operating in the ultraviolet (UV) spectral range and those used for high power, high frequency electronic devices require wider band-gap materials, and Al\textsubscript{x}Ga\textsubscript{1-x}N with increasing AlN content (x ≥ 0.5) is often the material of choice (Amano et al., 2020). It is challenging to effectively dope Al\textsubscript{x}Ga\textsubscript{1-x}N, with Si and Mg at such high AlN contents because as the bandgap increases the ionization energies also increase. At the same time, a very high Si doping concentration is needed to achieve low resistivity Al\textsubscript{x}Ga\textsubscript{1-x}N layers (Mehnke et al., 2016; Foronda et al., 2020).

The procedure of quantitative measurement of Si concentration in semiconductor layers will enable the optimization of growth conditions in order to achieve high efficiency devices. In this paper, wavelength-dispersive X-ray (WDX) spectroscopy within an electron probe microanalyser (EPMA) was employed to measure donor levels. The WDX technique is routinely used for the quantification of major elements (concentration > 1,000 ppm) and minor elements (100–1,000 ppm), and during the last decade, it has been successfully used for trace-element analyses (below 100 ppm and down to 10 ppm) (Donovan et al., 2011). WDX analysis has several advantages over other analytical methods such as dynamic secondary ion mass spectrometry (D-SIMS), energy-dispersive X-ray spectroscopy (EDX), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and micro particle-induced X-ray emission (μ-PIXE). These include high lateral spatial resolution (sub-μm), its nondestructive nature and that it does not usually require extensive standards due to the existence of well-developed matrix correction procedures. In addition, the EPMA allows acquisition of other analytical signals simultaneously with the high-resolution composition mapping, such as cathodoluminescence (CL; Martin et al., 2004; Lee et al., 2005; Edwards & Martin, 2011; Edwards et al., 2012),...
electron beam-induced current (EBIC; Wallace et al., 2014), and electron channeling contrast imaging (ECCI) signals (Naresh-Kumar et al., 2020). Some limitations of the WDX technique are that depth resolution is a function of the electron accelerating voltage, which must be high enough to excite all the relevant X-ray lines, preferably with an overvoltage ratio of at least 2 to ensure accurate analysis, particularly when approaching detection limits. These limitations also introduce constraints on the minimum sample thickness (Newbury, 2002) and depth profiling, where SIMS performs strongly including for nitride semiconductor structures (Martin et al., 2006; Wei et al., 2014; Michałowski et al., 2019; Pickrell et al., 2019). Two of these works employed time-of-flight SIMS (TOF-SIMS) which has a number of advantages over D-SIMS, including dual-source depth profiling where the two ion beams have been optimized for their respective tasks, although work is needed to achieve the same detection limit for dopants (Klump et al., 2018).

The capability of the WDX technique for measuring dopants within semiconductor epilayers has been reported by Deatcher et al. (2006) and Kusch et al. (2017). The latter compared WDX data for Si concentration ranges 40–350 ppm $(3 \times 10^{18}$–$2.8 \times 10^{19} \text{ cm}^{-3})$ in Al$_{x}$Ga$_{1-x}$N with commercially performed D-SIMS on some of the samples in the study. Both measurement methods showed the same general trend: a linear increase in the Si concentration with increasing SiH$_4$/III (silane to group-III ratio), but the Si concentration measured by WDX was higher by a factor of approximately 2 compared with D-SIMS. The reason for the discrepancy between the different types of measurement was not clarified at the time (Kusch et al., 2017). However, the reports in Deatcher et al. (2006) and Robin et al. (2016) show that it is possible to use X-ray microanalysis to measure doping levels in semiconductor epilayers, with Robin et al. using EDX to address quantitation of dopants. The report of Deatcher et al. (2006) shows that Mg measurement in GaN gives very good agreement between WDX and D-SIMS. The question of why WDX measurement appears to over-estimate values for the Si doping is the subject of this investigation. Donovan et al. (2011) developed optimum measurement practices for WDX trace analysis which we will apply in the analysis of Si doping.

Over the years, many research groups have addressed the trace-element capabilities of the WDX technique. Some early examples include the analysis of Ge distribution in iron meteorites (Goldstein, 1967), transition elements in ferromagnesin silicate minerals (Merlet & Bodinier, 1990), trace elements in minerals (McKay & Seymour, 1982), and trace elements in glass (Fialin et al., 1999). More recent works focus on specific situations or on refinements of the technique and conditions for trace analysis, such as the works from Allaz et al. (2019), Batanova et al. (2018), Buse et al. (2018), Carpenter et al. (2002), Donovan et al. (2011, 2016), Fournelle (2007), von der Handt et al. (2016), Jercinovic et al. (2005, 2012), Reed (2000, 2002), Sato et al. (2007), and Zhang et al. (2016).

In this paper, we will consider how to measure Si, at dopant levels, in semiconductor epilayers such as GaN and Al$_x$Ga$_{1-x}$N where inherent contamination of the sample surfaces with additional Si is suspected to be the cause of a discrepancy between the results from D-SIMS and WDX. Si incorporation is known to be a contaminant during the metal-organic chemical vapor deposition (MOCVD) growth of GaN and Al$_x$Ga$_{1-x}$N (Koleske et al., 2002). After removing a sample from the growth chamber, silicate dust in the air and silicone oils are a likely source of Si contamination of the surfaces. SIMS data for samples where there has been a growth interruption to allow transfer between reactors reveal contamination with Si. This is illustrated in Figure 1 for an AlGaN:Si layer grown in two stages. The spike in the Si trace at a depth of approximately 500 nm shows a significant increase in its concentration at the interruption interface. Such a spike has also been observed in samples where there is no Si doping as well as ones where there was simply a pause in epitaxy, with no change in the reactor, to allow changes in growth parameters such as temperature and pressure. SIMS profiles from Pickrell et al. (2019) reveal significantly greater Si concentration in GaN due to air contamination when compared with growth interruptions with temperature ramps. In both cases, the oxygen trace remained at the detection limit.

Furthermore, a number of groups fabricating GaN-based nanowires have discussed Si-rich layers forming on the surface of nanowires grown with high silane flows and which impact the lateral-to-vertical growth rates (Tessarek et al., 2014; Ren et al., 2018). These layers are clearly visible in EDX maps obtained using transmission electron microscopy and although only a few nm thick contain high concentrations of Si.

**Materials and Methods**

The aim of this study was to explore the use of WDX in a commercial EPMA (JEOL JXA-8530F) to simultaneously measure the concentration of major (alloy) and minor (dopant) elements within semiconductor epilayers at specific points on the sample surface. We demonstrate a new approach to correct for the
overestimation in measured Si donor concentration caused by inherent contamination of the sample surfaces with additional Si.

A range of Si-doped GaN and Al$_x$Ga$_{1-x}$N samples, grown by MOCVD by different groups, were used to clarify the best way to measure Si. GaN:Si material (sample EU2000894) was provided by IQE Europe Ltd. A series of Al$_x$Ga$_{1-x}$N samples with different crystal polarities and different AlN contents was provided by the Tyndall Institute. These Al$_x$Ga$_{1-x}$N samples included polar-oriented [0001] (samples AP, BP, CP) and semipolar-oriented layers [112-2] (samples ASP, CSP). More details on the growth of the Al$_x$Ga$_{1-x}$N layers from the Tyndall Institute are given elsewhere (Li et al., 2013; Dinh et al., 2016a, 2016b; Pampili et al., 2018; Spasevski et al., 2021). Samples labeled TS are Al$_x$Ga$_{1-x}$N layers with various AlN contents and crystal polarities grown on Technische Universität Berlin (Knauer et al., 2013; Kusch et al., 2014; Mehneke et al., 2016; Foronda et al., 2020). The “blank” Al$_x$Ga$_{1-x}$N TS5541 was grown with no Si doping and quickly shipped in a sealed container filled with N$_2$ gas in order to minimize contamination and on receipt it was immediately placed under vacuum within the EPMA chamber. Information on the three sets of samples is given in Tables 1 and 2. Attempts were made to remove inherent surface contamination by oxygen plasma cleaning treatments. Traditionally, plasma cleaning is employed to remove hydrocarbon contamination (Donovan & Rowe, 2005). Apart from contamination, the samples can also suffer from oxidation. To investigate the effect of oxidation of the Si standard, cleaning with HF solution was employed. D-SIMS data were provided by three different companies: RTG Mikroanalyse GmbH Berlin (Jörchel et al., 2016), Loughborough Surface Analysis Ltd. (using a Cameca 7f), and Evans Analytical Group (EAG). All samples were analyzed in a depth profile mode, using areas typically $100 \times 100 \mu m^2$. RTG used ion-implanted AlGaN samples to produce absolute and relative sensitivity factors for Si in AlGaN, with further details given in Jörchel et al. (2016). The same approach was used for data from Loughborough. EAG used a proprietary method that calculates the change in sensitivity factors with respect to the AlN fraction in AlGaN.

D-SIMS measurements were performed in the EPMA with the incident electron beam normal to the sample surface, and an acceleration voltage of 10 kV which is sufficient to efficiently excite the selected X-ray lines. Under these conditions, the electron interaction volume is kept within the first 500–800 nm of the Al$_x$Ga$_{1-x}$N layer according to Monte Carlo simulations using CASINO software (Drouin et al., 2007) and dependent on the AlN molar content. In all samples, the interaction volume is contained within the topmost Al$_x$Ga$_{1-x}$N layer. The beam current was 40 nA for analysis of the major elements (Al, Ga, N) and increased to 400–500 nA for the minor elements. The beam was defocussed to 10 or 20 μm to improve sample averaging and avoid damaging the sample. The samples and standards were carbon coated to remove charging effects, with a thickness of approximately 15 nm [as determined by the interference-color method of Kerrick et al. (1973)]. This becomes increasingly important for AlN-rich Al$_x$Ga$_{1-x}$N for which the conductivity decreases. Measurements were also performed on
two of the GaN:Si sample without coatings (and using uncoated standards) to confirm that the coating was not a source of Si.

According to best practice for trace analysis, the pulse height analysis (PHA) parameters (such as voltage window, baseline, electronic bias, and gain on the detector) were adjusted before analysis (PHA) parameters (such as voltage window, baseline, standards) to confirm that the coating was not a source of Si.

Table 2. List of Al<sub>1</sub>Ga<sub>1</sub>N Samples for Which Independent Constraint on the Composition Is Not Available, Measured AlN at.% Using WDX and Si K<sub>α</sub> Intensity Values Together with the Calculated Si Concentration [Crystal Orientation [0001] AxP, Orientation [1122] AxSP].

<table>
<thead>
<tr>
<th>Sample name</th>
<th>WDX AlN at.%</th>
<th>WDX Si net (cps/μA)</th>
<th>Calculated ZAF factor for the Si K&lt;sub&gt;α&lt;/sub&gt; in Al&lt;sub&gt;1&lt;/sub&gt;Ga&lt;sub&gt;1&lt;/sub&gt;N</th>
<th>Calculated Si concentration (10&lt;sup&gt;18&lt;/sup&gt; cm&lt;sup&gt;-3&lt;/sup&gt;) using the calibration method and calcZAF software</th>
<th>Calculated Si concentration (ppm) using the calibration method and calcZAF software</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1SP</td>
<td>56.6 ± 0.6</td>
<td>175 ± 16</td>
<td>1.283</td>
<td>3.1</td>
<td>31</td>
</tr>
<tr>
<td>A2SP</td>
<td>65.5 ± 0.7</td>
<td>440 ± 13</td>
<td>1.289</td>
<td>5.7</td>
<td>61</td>
</tr>
<tr>
<td>A3SP</td>
<td>61.2 ± 0.7</td>
<td>469 ± 54</td>
<td>1.286</td>
<td>6.2</td>
<td>65</td>
</tr>
<tr>
<td>A4SP</td>
<td>59.4 ± 0.7</td>
<td>463 ± 19</td>
<td>1.285</td>
<td>6.2</td>
<td>64</td>
</tr>
<tr>
<td>A5SP</td>
<td>59.6 ± 0.7</td>
<td>374 ± 10</td>
<td>1.285</td>
<td>5.2</td>
<td>54</td>
</tr>
<tr>
<td>A1P</td>
<td>63.0 ± 0.7</td>
<td>218 ± 33</td>
<td>1.287</td>
<td>3.4</td>
<td>36</td>
</tr>
<tr>
<td>A2P</td>
<td>71.7 ± 0.8</td>
<td>253 ± 22</td>
<td>1.294</td>
<td>3.5</td>
<td>40</td>
</tr>
<tr>
<td>A3P</td>
<td>68.8 ± 0.7</td>
<td>320 ± 6</td>
<td>1.292</td>
<td>4.3</td>
<td>47</td>
</tr>
<tr>
<td>A4P</td>
<td>62.7 ± 0.7</td>
<td>534 ± 9</td>
<td>1.287</td>
<td>6.8</td>
<td>72</td>
</tr>
<tr>
<td>A5P</td>
<td>69.3 ± 0.7</td>
<td>743 ± 9</td>
<td>1.292</td>
<td>8.6</td>
<td>96</td>
</tr>
</tbody>
</table>

Results and Discussion

In order to test the detection limit of approximately 10 ppm (1σ), which corresponds to concentrations of 10<sup>18</sup> cm<sup>-3</sup> of Si in GaN, we performed WDX measurements on two GaN: Si samples (TS4142 and TS4137) with low silicon contents that were also characterized by SIMS (Table 1), and on one “blank” Al<sub>1</sub>Ga<sub>1</sub>N sample TS5541. Figure 2 shows long qualitative WDX scans (dwell time 12 s, 505 points, total time: 1 h 36 min), which were performed to check for the existence of the Si K<sub>α</sub> peak. A Si peak is clearly visible above the background level in all of the above-mentioned samples (even in the “blank” sample, referred from now on as a control sample) and much greater than error/ detection limit. We conclude that sample TS5541 is not actually blank and has accrued Si either during growth or in the time before measurement. From the qualitative scans, it is also possible...
to conclude that there are no signs of any interference close to the Si Kα peak that could be a serious source of error in quantitative microanalysis and that the peak position is the same in the tested samples (Donovan et al., 1993). There are differences in the shape of the background for the samples shown in Figure 2, with the main difference being the high Al content in TS5541 which could be responsible for the increased background on the high-energy side for this sample.

Since the SIMS measurements (for the GaN samples) gave values below or close to the detection limit, the silicon doping should have been unmeasurable in these cases. However, the WDX data show clear Si X-ray peaks and high apparent Si content (>6 × 10¹⁸ cm⁻³) compared with <7 × 10¹⁷ cm⁻³ from the SIMS value in Table 1). Furthermore, the WDX analysis returned a similar value for Si concentration from the control sample. Measurements performed at the University of Bristol for GaN samples (TS4142 and TS4137, Table 1) gave similar Si concentrations (×1.6 and ×2 higher, respectively). A different set of analytical conditions was used for the measurement, with a 400 nA current and 10 μm spot size. The above results appear to confirm that the samples are contaminated with Si in a way that would prevent convergence of the WDX and SIMS results by any simple adjustment of the analysis conditions. Thus, as far as we can tell, cleaning treatments did not remove possible Si contamination and that oxidation of the sample or standard is not the reason for the large discrepancy between SIMS and WDX results. The data measured from two GaN:Si samples, with and without C-coating, confirms that the C-coat is not the source of extra Si.

After cleaning the Si standard, calibration data was acquired from it using a very low current of 1 nA in order to reduce the count difference between the standard and unknown trace element. This did not result in any difference in the measured concentration for the trace element when compared with calibration data acquired with 20 nA. Subsequently, all calibration data are acquired with a lower beam current of 20 nA compared with the 500 nA employed to measure Si in the unknowns, in order to avoid detector over saturation. In doing this, we have relied on the current measurement system scaling linearly from 20 to 500 nA.

Table 3. Si Kα Intensities Acquired for Pure Si Standard, Before and After Removal of Native Oxide Layer.

<table>
<thead>
<tr>
<th>TAPL crystal, 20 nA, 10 kV</th>
<th>Before cleaning (counts)</th>
<th>After cleaning (counts)</th>
<th>Percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>76,313</td>
<td>79,353</td>
<td>4</td>
</tr>
<tr>
<td>Coated</td>
<td>78,596</td>
<td>80,823</td>
<td>3</td>
</tr>
</tbody>
</table>

Due to the long measurement time and high currents used for the silicon analysis, the instrumental and sample stability need to be checked (Hughes et al., 2019). A sample will generally be stable during analysis with usual operating conditions (10–100 nA), but the high currents (hundreds of nA) required for trace-element analysis may cause it to degrade (Carpenter et al., 2002). It is necessary to assess if the samples are stable during measurement time due to potential charge build-up, heating or radiation damage. This was assessed by monitoring the count rate for Si Kα in one of the calibration samples at the same time as the absorbed current. Figure 3 shows that the silicon signal remains stable during the long counting times and there is only a very slight decrease of the absorbed current (0.3%). Since the measured absorbed current is not showing a significant drop or oscillations, it implies that the electrical properties of the coating are sufficient. The time scan was performed with a 10 μm defocused beam to simulate more extreme conditions, while the quantitative analysis sometimes used a beam diameter of 20 μm in order to minimize any absorbed current instability (Jercinovic & Williams, 2005).

Another possible reason for high Si values could be the existence of surface layers of native oxide formed on the standards. Oxidation of the standard will form native layers of oxygen on the surface. Therefore, cleaning in HF solution was employed to remove the oxide layer from the Si standard. Qualitative scans around the Si peak were performed before and after cleaning (not shown), and Si Kα intensity data were acquired on the Si standard before and after the cleaning to check the difference (Table 3).

Table 3 shows that removal of the oxidation layer from the standard did not produce any significant changes (only 3–4%) in the intensity of Si Kα peak. We can assume that the native oxygen layer was thinner than 10 nm (Carpenter, 2008).

Thus, as far as we can tell, cleaning treatments did not remove possible Si contamination and that oxidation of the sample or standard is not the reason for the large discrepancy between SIMS and WDX results. The data measured from two GaN:Si samples, with and without C-coating, confirm that the C-coat is not the source of extra Si.

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The results of all the tests described so far lead us to propose that the best solution for using WDX for the accurate measurement of doping in Al₃Ga₁₋ₓN samples is to generate a calibration relation using samples also characterized by D-SIMS. The results listed in Table 1 are plotted in Figure 4 and show that the Si net intensity value (peak minus background) does not go below about 200 cps/μA even for the samples with very low Si contents, which we attribute to surface contamination with Si (samples TS4142, TS4137, TS5541). These samples (marked by the gray circle) are thus considered not suitable for calibration and we propose a calibration relation for Si concentrations down to a lower limit defined by an Si net value of 200 cps/μA. Prior to generating this line, the impact of the host material must be accounted for as these samples consist of Al₃Ga₁₋ₓN with different AlN% contents (Table 2).
The change in matrix correction (ZAF correction) for Si for different AlN contents was estimated using the stand-alone CalcZAF software (Donovan et al., 2019), as plotted in Figure 5. The different correction procedures available in CalcZAF software did not produce a noticeable difference in the correction factors.

The calculated ZAF parameters are then used to adjust all the D-SIMS calibration points to the effective value for a GaN host, as shown in Figure 6. This resulting calibration relation allows the Si content to be estimated in samples of all Al\textsubscript{x}Ga\textsubscript{1−x}N compositions by measuring the Si intensity, then using the GaN calibration curve with the appropriate ZAF correction.

This process is illustrated using the series of Al\textsubscript{x}Ga\textsubscript{1−x}N samples listed in Table 2. The measured intensity values, Si net (cps/μA), are adjusted to the effective Si net values for GaN, using the ZAF correction procedure, and these are then converted to Si concentration using the calibration curve. The calculated Si concentrations in Al\textsubscript{x}Ga\textsubscript{1−x}N are plotted in Figure 7, which also shows the calibration line for GaN for comparison. This method enables the Si concentration in Al\textsubscript{x}Ga\textsubscript{1−x}N samples of any composition to be estimated by measuring the Si intensity. For samples with Si net ≤200 cps/μA (e.g. sample A1SP), the equivalent Si concentration is set to the sensitivity limit of 35 ppm, which corresponds to concentrations ranging from 2.4 × 10\textsuperscript{18} cm\textsuperscript{−3} for AlN or 4.6 × 10\textsuperscript{18} cm\textsuperscript{−3} for GaN, calculated from the calibration curve in Figure 6.

Figure 8 plots the calculated Si concentrations against the disilane to group III ratios (Si\textsubscript{2}H\textsubscript{6}/III ratios) (Dinh et al., 2016\textsuperscript{a}, 2016\textsuperscript{b}; Pampili et al., 2018). In MOCVD growth, the group III atoms are introduced via metal precursors in the form of organic compounds such as trimethylgallium and trimethylaluminium, while ammonia is the nitrogen source. Doping can be obtained by introducing into the reactor dopant-containing gases, such as disilane (Si\textsubscript{2}H\textsubscript{6}) (Pampili & Parbrook, 2017). The measured Si concentrations for the semipolar ASP samples increase linearly with the Si\textsubscript{2}H\textsubscript{6}/III ratio up to a saturation point of 2.3 × 10\textsuperscript{−4}.
group III ratio, as evaluated by WDX. The solid lines provide guides to the eye. Si$_2$H$_6$/III ratio. The AP series exhibits an almost linear mobility of semipolar layers were observed to reach a maximum from this line according to the amount of AlN contained in the host material. The saturation point is consistent with a previous report Fig. 8.

Si concentration of the Al$_x$Ga$_{(1-x)}$N-doped layer as a function of disilane to group III ratio, as evaluated by WDX. The solid lines provide guides to the eye. Si$_2$H$_6$/III. The saturation point is consistent with a previous report from Dinh et al. (2016a), where the carrier concentration and mobility of semipolar layers were observed to reach a maximum at a similar Si$_2$H$_6$/III ratio. The AP series exhibits an almost linear increase of Si with disilane flow rate.

Summary

The use of WDX spectroscopy for the measurement of silicon-doping levels in wide band-gap Al$_x$Ga$_{(1-x)}$N layers is demonstrated in a commercially available EPMA instrument. A previously reported limitation with over-estimates of the Si contents was thoroughly investigated and was assigned to surface contamination. An analytical routine was introduced for measuring the trace Si levels, consisting of separate measurement of Si with high current and long counting times followed by calibration using D-SIMS measurements. By measuring silicon intensities and using a calibration curve fit method using the D-SIMS data along with calculated ZAF correction values, it was possible to determine doping levels of order (3–10) × 10$^{18}$ cm$^{-3}$ in Al$_x$Ga$_{(1-x)}$N layers with varying AlN contents and polarity. The highest values of Si incorporation were observed for polar samples (100 ppm), while saturation of Si incorporation was seen for semipolar samples at a high Si/III ratio. The advantages of the WDX approach include high lateral spatial resolution and the ability to determine the alloy composition of the major elements, such as Al, Ga, and N, at the same time as the doping levels. The standards used in WDX analysis are more accessible compared with ion-implanted standards required for the SIMS analysis. Apart from the quantitative abilities of the EPMA instrument, another major advantage in the examination of the semiconductor alloys is the correlation of WDX data with other microscopy techniques such as CL and ECCI as well as the high-resolution mapping capabilities.

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