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HIGH BREAKDOWN VOLTAGE GaN p-n DIODE

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Vertical structured GaN power devices have recently been attracting great interest because of their potential on extremely high power conversion efficiency. This letter describes increased breakdown voltages in vertical GaN p-n diodes fabricated on free-standing GaN substrates. By applying multiple lightly Si doped n-GaN drift layers to the p-n diode, record breakdown voltages (V_B) of 4.7 kV combined with low specific differential on-resistance (R_{on}) of 1.7 mΩcm^2 were achieved. With reducing the Si-doping concentration of the top n-GaN drift layer adjacent to the p-n junction using well-controlled MOVPE systems, the peak electric field at the p-n junction could be suppressed under high negatively-biased conditions. The second drift layer with a moderate doping concentration contributed to the low R_{on}. Baliga's figure of merit ($V_B{}^2/R_{on}$) was 13 GW/cm^2. These are the best values ever reported among those achieved by GaN p-n junction diodes on free-standing GaN substrates.

I. Introduction

Gallium Nitride (GaN) has been well recognized as the material whose electrical parameters are ideally suited for power devices as well as high frequency devices. Horizontal structured GaN power switching devices such as MIS-FETs have already been commercially available. However, their power conversion efficiency and current drivability are limited because of their very high lattice-misfit dislocation densities caused by hetero-epitaxy on foreign substrates such as Si and SiC. Recent progress in crystalline quality and productivity of free-standing GaN substrates has enabled rapid development of vertical structure devices, which can extract the GaN's full potentials for the power-conversion applications. GaN p-n diodes with high breakdown voltages around 3 kV showed the Baliga's figure of merits (FOM) by approximately one order of magnitude larger than those of SiC Schottky-barrier diodes [1-3)].

We have adopted damage-free process for formation of field-plate (FP) electrodes which enabled low on-resistance (R_{on}), low forward on-voltage and high breakdown voltages[2, 4-5)]. Here we report 1 kV increase of the breakdown voltage over the record value[3)] by using multiple lightly Si doped n-GaN drift layers in which the top n-GaN drift layer has the lowest Si-doping concentration in order to reduce the peak electric field at p-n junction.

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II. Experimental

The detailed schematic structure of the p-n diode is shown in Fig.1. The layer structure shown in the figure was grown by metal-organic vapor phase epitaxy (MOVPE) on a free-standing GaN substrate fabricated by the void-assisted separation method with threading dislocation densities less than 3×10^6 cm^{-2} [6-7]. Electron density, mobility, diameter and thickness of the used substrate were 1.5×10^{18} cm^{-3}, 40 cm^2/Vs, 2 inch and 0.4 mm, respectively. Trimethylgallium (TMG), ammonia (NH_3), bicyclopentadienyl-magnesium (Cp_2Mg), and silane (SiH_4) were used as precursors. Drift layers under the p-GaN layer consist of undoped GaN with a residual Si concentration of $< 2 \times 10^{15}$ cm^{-3}, n$^-$-GaN with a Si concentration of 9×10^{15} cm^{-3}, and n$^-$-GaN with a Si concentration of 1.6×10^{16} cm^{-3}. The low Si doping was performed using our specially designed diluted silane gas lines. By reducing the doping concentration underneath the p-GaN layer, the peak electric field at the p-n interface can be suppressed under negatively biased conditions. The Si-doping profile of the triple drift layers was confirmed by Secondary Ion Mass Spectrometry (SIMS) analysis as shown in Fig.2. The Si concentration in the undoped GaN layer was revealed as 2×10^{15} cm^{-3} by the SIMS analysis, however, the value was close to the detection limit and the actual Si concentration was thought be smaller. Another layer structure with double drift layers consisting of the undoped layer (2 μm) and n$^-$-GaN layer with a Si concentration of 1.1×10^{16} cm^{-3}(22 μm) was also grown for comparison. Electric field in the two type of drift layers were calculated by simple 1-D Poisson's equation considering that a certain amount of Si donors were compensated by residual impurities. Figure 3 shows the electric fields under -6 kV biased condition for the triple-drift-layer structure and -4 kV biased condition for the double-drift-layer structure. Under these conditions, the peak electric field reached 3.3 MV/cm where

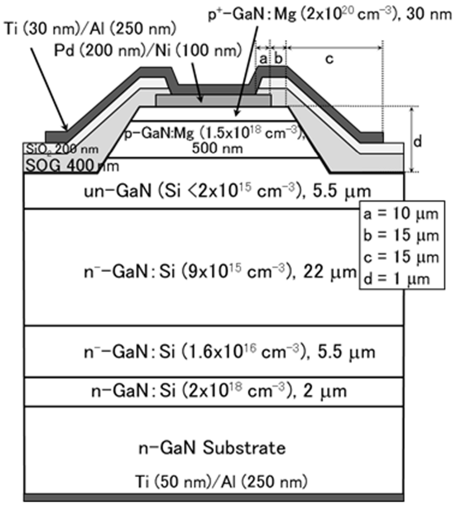

Fig.1. Schematic cross sections of the GaN p-n junction diodes with the triple drift layers and the FP structure.

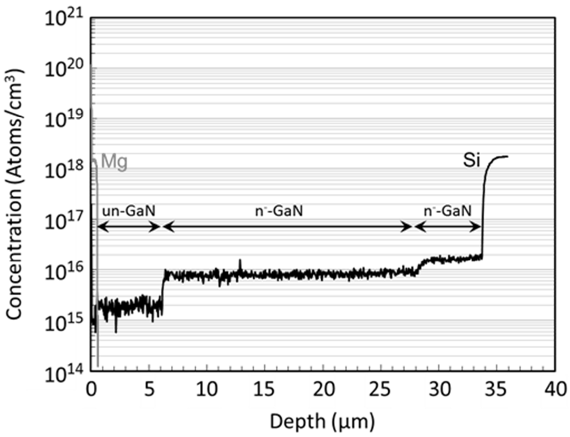

Fig.2. Si and Mg doping profiles of the epitaxial wafer for the GaN p-n junction diode measured by Secondary Ion Mass Spectrometry (SIMS) analysis.

the breakdown is supposed to occur in GaN. After the MO-VPE, thermal annealing was performed at 850 ºC for 30 minutes under N_2 ambient in order to activate Mg acceptors by removing adherent hydrogen atoms.

The FP electrode structure using the SiO_2-covered spin-on-glass (SOG) film has already been reported to be effective for reducing reverse-leakage current and increasing breakdown voltage[4-5]. The SOG film was suitable for a mild passivation against damage caused by plasma during SiO_2 sputtering deposition, which resulted in excellent ohmic contacts to the p-GaN layer. The procedure of fabricating the diode structure was mentioned in detail elsewhere[2]. The diameters of the circular Pd ohmic electrode were 60-200 μm and these values were used for calculation of R_{on} because lateral current spreading could not be estimated properly even by using three-dimensional simulation at the moment. Current-voltage (I-V) characteristics were evaluated using Agilent B1505A combined with an ultra-high-voltage unit at room temperature while samples were immersed in insulating oil.

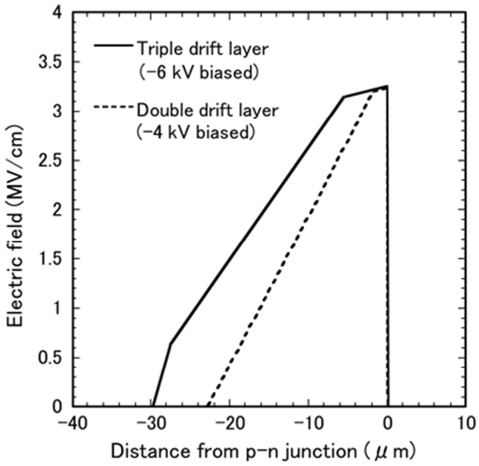

Fig.3. Electric fields calculated by 1-D Poisson's equation under -6 kV biased condition for the triple-drift-layer structure and -4 kV biased condition for the double-drift-layer structure.

III. Results and discussions

Figure 4 shows forward I-V characteristics of the diodes with the triple and double drift layers. The circular ohmic electrode's size was 100 μm in diameter. The turn-on voltages of the diodes were about 3.1 V as expected from a diffusion potential of the GaN p-n junction. R_{on}'s were low as 1.7 and 1.4 mΩcm^2 for the diodes with triple and double drift layers, respectively, as plotted in Fig.4. These low R_{on}'s were brought by high quality epitaxial layers grown on the GaN substrates with low dislocation density. The high quality layers enhances photon-recycling effect which increases conductive

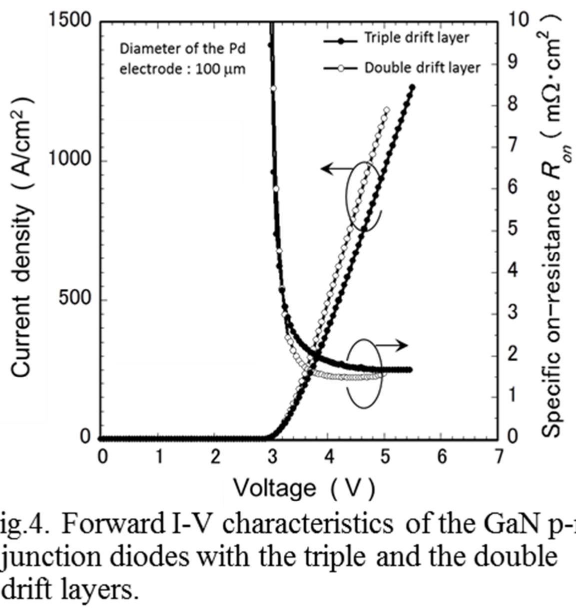

Fig.4. Forward I-V characteristics of the GaN p-n junction diodes with the triple and the double drift layers.

holes from deep Mg acceptors excited by high-density photons generated through electron-hole-pair recombination at the p-n junction[8,9]. This effect brings a strong advantage to GaN p-n diodes in lowering the R_{on} by GaN's nature as a direct-energy bandgap semiconductor. Carrier lifetime could be estimated as 9 ns by g-r current behavior at the range of 2-2.5 V.

Figure 5 shows the reverse I-V characteristics of the GaN p-n junction diodes with the triple drift layers. The breakdown voltage as high as 4.7 kV was obtained for the diodes with the Pd electrode diameters of 60-200 μm. The value is 1.0 kV higher than the one in the previous report using a single-drift-layer structure [3]. The breakdown voltage of the diode with the simpler double drift layer was also high (3.8 kV). These results exhibited the effectiveness of employing the multiple drift layers, which could reduce the peak electric field at the p-n interface. It might be possible to obtain a similar or higher breakdown voltage if a single undoped GaN thicker layer is used instead of the multiple drift layer, however, the R_{on} would increase largely because the conductive electrons at the forward-biased condition are lacking. Hence, the particular drift layer of this study was shown to be effective in raising the total performance of GaN p-n diodes. The discussions can be clearly supported by Fig. 6, which shows the plot of the R_{on} versus the breakdown voltage V_B for comparing power-device figure-of-merit in the previous works. The Baliga's figure-of-merit (V_B^2/R_{on}) [10] resulted in this study was 13 GW/cm^2. These are the best values ever reported among those achieved by GaN p-n junction diodes on free-standing GaN substrates. Further improvement of the V_B toward the value by the 1-D Poisson's calculation can be expected by refining the processing of insulating films and FP electrodes because every breakdown in this study occurred at the mesa edge or FP-electrode edge of the diodes.

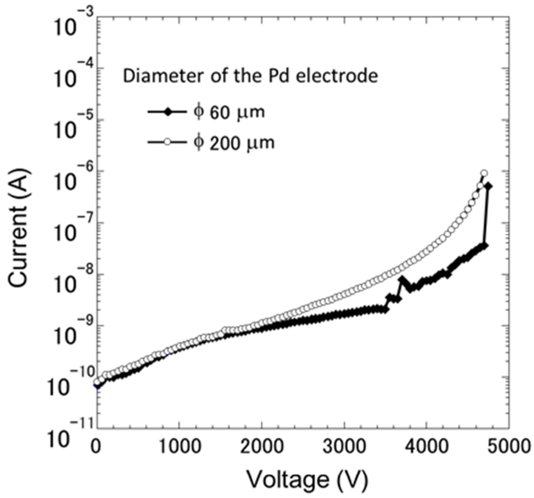

Fig.5. Reverse I-V characteristics of the GaN p-n junction diodes with the triple drift layers.

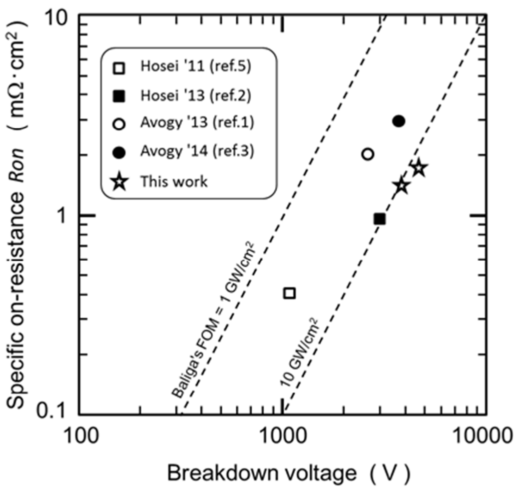

Fig.6. Relationship between the specific on-resistance and breakdown voltage of the GaN p-n junction diodes fabricated in this study with previously reported results.

IV. Conclusions

The record high breakdown voltage of 4.7 kV in vertical GaN p-n junction diodes was achieved by introducing the multiple drift-layer structure fabricated on free-standing GaN substrates. By reducing Si-donor concentration in the top n-GaN drift layer underneath the p-GaN layer, the peak electric field was suppressed. The structures were shown to be effective in improving both the breakdown voltage and R_{on} resulting in the Baliga's figure-of-merit of 13 GW/cm^2. This result can be a distinct advantage of vertical structure GaN power devices.

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