# ULTRA-LOW ON-RESISTANCE p-n JUNCTION DIODES FABRICATED ON HEAVILY Ge-DOPED GaN SUBSTRATE.

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# ULTRA-LOW ON-RESISTANCE p-n JUNCTION DIODES FABRICATED ON HEAVILY Ge-DOPED GaN SUBSTRATE.

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p-n junction diodes were fabricated on heavily Ge-doped (≥ 6×10$^{18}$ cm$^{-3}$) GaN substrates. A significant reduction in forward on-resistance was observed compared to p-n diodes on a conventional Si-doped (2×10$^{18}$ cm$^{-3}$) GaN substrate. No significant difference was observed in reverse breakdown voltage of each sample. In addition, by applying the heavily doped substrate, it became possible to minimize the dependence of the forward current density on the diameter of the anode electrode. Highly Ge-doped GaN substrates have been found to be very useful for the fabrication of low on-resistance GaN power devices with a large size.

## I. Introduction

Vertical GaN power devices are attracting attention due to the superior potential of high efficiency power conversion systems. In this study, mesa-structure p-n junction diodes were fabricated on heavily Ge-doped GaN substrates with very high electron concentrations, and the impacts on forward on-resistance and reverse breakdown characteristics were investigated.

## II. Experimental methods

Figure 1 shows the cross-sectional structure of the p-n diode. The epitaxial layers with p$^+$-GaN(Mg= 2 × 10$^{20}$ cm$^{-3}$, 30 nm)/p-GaN(Mg = 1 × 10$^{18}$ cm$^{-3}$, 500 nm)/n-GaN(Si=7×10$^{15}$ cm$^{-3}$, 13 μm)/n-GaN(Si =2×10$^{18}$ cm$^{-3}$, 2 μm) were grown by a multiple-wafer type metal-organic vapor-phase epitaxy (MOVPE) reactor on the heavily Ge-doped GaN substrate with doping concentrations of 6×10$^{18}$ cm$^{-3}$ (G1) and 8×10$^{18}$ cm$^{-3}$ (G2) and on a conventional Si-doped GaN substrate with a doping concentration of 2×10$^{18}$ cm$^{-3}$ (S1). The three substrates were fabricated by the void-assisted separation (VAS) method using hydride vapor-phase epitaxy (HVPE) [1)] and their threading dislocation densities were comparable to one another (TDD≒3×10$^{6}$ cm$^{-2}$). 2-step mesa structure which enabled an excellent avalanche capability was applied for the p-n diode [2)]. The diameters of the anode electrodes were 60, 100, 200, 400 and 800 μm. The first mesa was formed 5 μm outside

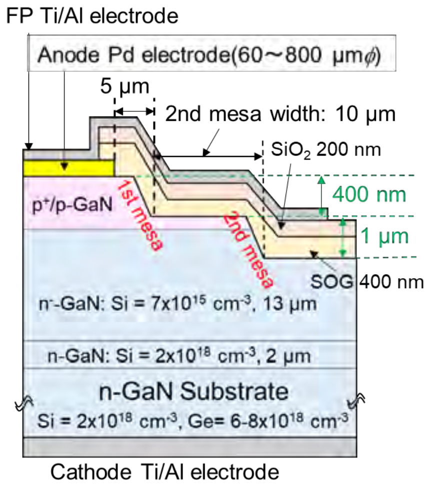


Fig. 1. Half-cut schematic structure of p-n junction GaN diode.

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the circular electrodes by partial removal of the p-GaN layer. The second mesa was formed 10 μm outside the first mesa by additional etching down to the top region of the n-GaN drift layer.

## III. Results and discussion

Figure 2 shows forward I-V characteristics of p-n diodes fabricated on the differently doped GaN substrates. The forward current densities of the p-n junction diodes on S1, G1 and G2 with anode electrode diameters of 100 μm were 3.60, 4.69 and 6.41 kA/$cm^2$ at a forward voltage of 5.0 V, respectively. The corresponding specific on-resistances ($R_{on}$) were 0.279, 0.180, and 0.111 $m\Omega cm^2$. Considering breakdown voltages ($V_B$) which will be described later, Baliga's figure of merit ($BFOM = V_B^2/R_{on}$) were 12.3, 18.8 and 29.7 GW/$cm^2$, respectively. If $R_{on}$ of the diode on G2 at 5.3 V was applied to the BFOM, the value jumped up to 79 GW/$cm^2$. Figure 3 shows reverse I-V characteristics of the p-n diodes fabricated on the differently doped GaN substrates. The reverse breakdown with excellent reversible properties occurred at about 1800 V with little dependence on the substrates. The drastic improvement of the forward characteristics could not be explained simply by the lowered resistivity of the heavily doped substrates. TCAD simulation revealed that a large amount of injected electrons from the heavily doped substrates caused the significant conductivity modulation. Generally, in a vertical power device, current tends to concentrate at the electrode edge due to lateral-current spread in the substrate, and as a result, a diode having a large electrode diameter causes a decrease in current density calculated using the electrode area at the same voltage. This current-density dependence on the electrode size is a drawback in fabrication of large area devices. Figure 4 shows forward I-V characteristic dependence on diameter of anode electrode for the p-n junction diodes fabricated on the three different GaN substrates. However, it was experimentally

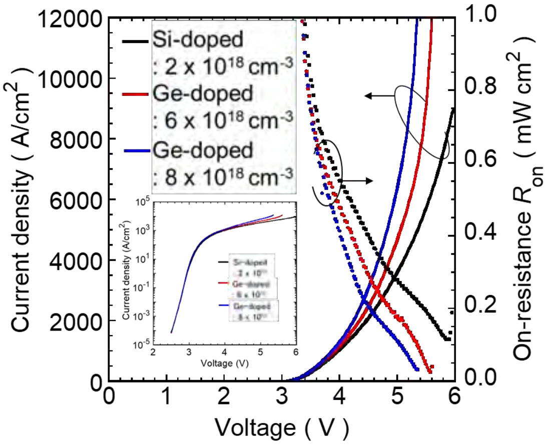


Fig. 2. Forward I-V characteristics of p-n diodes fabricated on the differently doped GaN substrates.

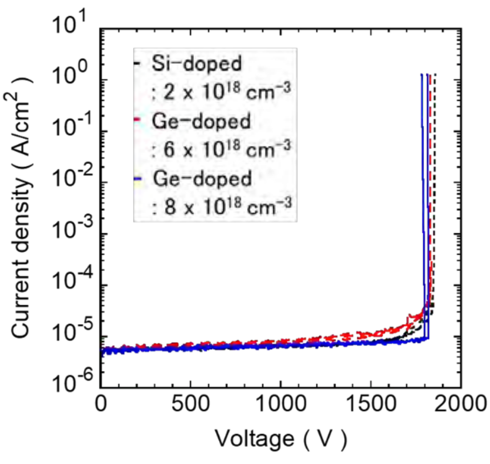


Fig. 3. Reverse I-V characteristics of p-n diodes fabricated on the differently doped GaN substrates.

observed that the dependence became much smaller for the diodes on the substrates with heavier doping. Figure 5 shows simulated distributions of electron concentration in the p-n diodes at forward voltage of 5 V and Fig. 6 shows simulated lateral distributions of current densities at drift layer depth of 7 μm under the p-n junction by TCAD. The analyses successfully gave an explanation to this behavior by occurrence of more uniform and higher injection of electrons from the heavier doped substrate.

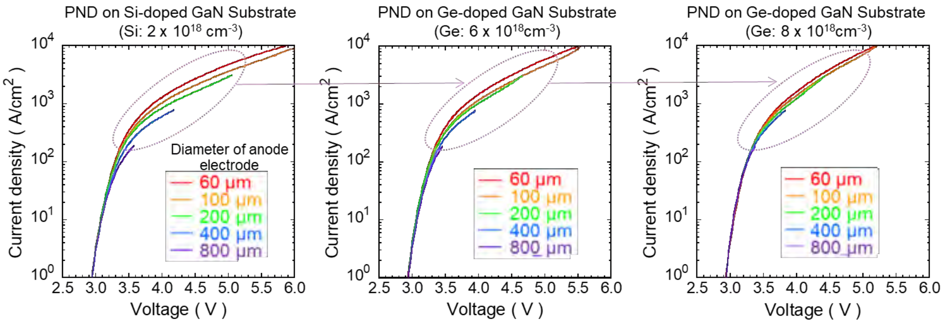


Fig. 4. Forward I-V characteristic dependence on diameter of anode electrode for the p-n junction diodes fabricated on the three different GaN

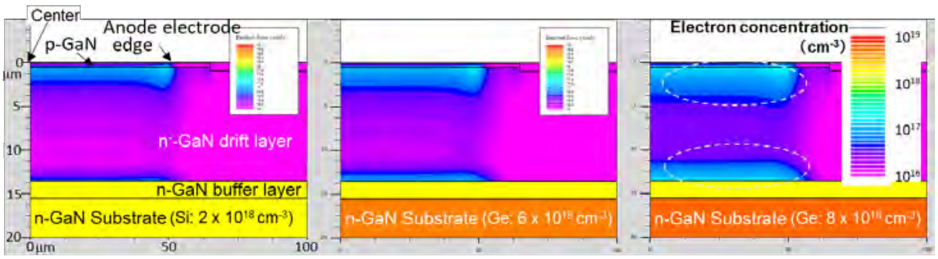


Fig. 5. Simulated distributions of electron concentration in the p-n diodes at forward voltage of 5 V.

## IV. Conclusions

We have fabricated p-n junction diodes on highly Ge-doped GaN substrates and compared them with those on a conventional Si-doped substrate. By applying the heavily doped substrate, it became possible to significantly reduce the on-resistance, and little difference was observed in the reverse breakdown voltage. In addition, by applying the heavily doped substrate, it became possible to minimize the dependence of the forward current density on the diameter of the anode electrode. It was found that heavily Ge-doped GaN substrates are extremely useful for fabricating large-sized low on-resistance GaN power devices.

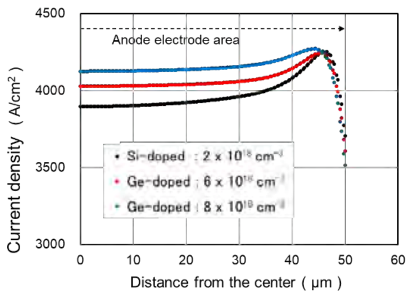


Fig. 6. Simulation result of lateral distribution of current density at drift layer depth of 7 μm.

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