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High Breakdown GaN Schottky Diodes with Buried P-layer Structure

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1. Introduction

GaN Schottky rectifiers play an important role in inverter modules owning to their high switching speed and low switching loss [1]. It has been shown that GaN-based Schottky diodes presented much better performance than their Si-based counterparts. Compared with the Si Schottky diodes, the GaN diodes demonstrated a high breakdown field (up to 3 MV/cm) and a low on-state resistance, which can be mainly attributed to the superior material properties of GaN [2]. Currently, most of the GaN-based devices are grown on sapphire or SiC substrates. For GaN Schottky diodes on sapphire, the low thermal conductivity could be a serious problem for high power applications, while those grown on SiC are mainly limited by the relatively high cost for commercial applications.

GaN epitaxy on silicon substrate seems to be an excellent alternative approach for the above problems, which has a good thermal conductivity and relatively low cost. In addition, the silicon substrate has the potential for large-scale growth of GaN epilayer. GaN-based devices on Silicon substrates have been reported with relatively low breakdown voltages (~ 100 V to 300 V) [3]-[4]. For these devices, the GaN layer thickness is only around 1 ~2 μm. On the other hand, it has also been reported that GaN devices on silicon demonstrated a high breakdown voltage of 650V, in which the GaN layer is up to 5 μm [4]-[5]. For high power applications, it is in general required to have a thick GaN layer (typically > 3μm) to sustain the high voltage operation. However, this may not be a good solution for improving the breakdown voltage especially for GaN grown on Si. Since there is a large lattice mismatch between Si and GaN, growing a thick GaN layer on Si could encounter serious crystal dislocation issues and thus reliability problems.

In this study, a new layer structure is proposed to significantly improve the breakdown voltage of the GaN Schottky diode on silicon substrate with only a 1.5 μm thick epi-layer, which can substantially reduce the electric field in the buffer layer. The layer structure employs a floating p-type GaN layer below the n-type GaN layer to form a buried pn-junction. The simulated results show that the buried pn-junction structure can improve the breakdown voltage from 130 V of the conventional device up to 4800 V by the proposed device structure.

2. Device Structures and Simulation Results

The layer structures of the typical GaN Schottky diode and the proposed new design are shown in Fig. 1(a) and 1(b), respectively. The conventional device consists of a 0.5 μm thick n-type GaN layer on top of a 1 μm undoped GaN buffer layer. On the other hand, the proposed layer structure consists of a 0.5 μm thick undoped GaN layer as the buffer, followed by a 0.5 μm p-type GaN layer (the buried p-layer), and a 0.5 μm thick n-type GaN is on top of the p-layer. Finally, both devices are passivated by a 1 μm silicon dioxide layer. The device layer structures are defined on silicon substrates in the simulation, and the Schottky metal work function is assumed to be 5.15 eV (Nickle) in the simulation. The proposed structure utilizes the concept of charge compensation by introducing a buried p-layer below the n-type GaN layer. The doping concentration and thickness of n-type and p-type are identical so that the number of average charges in the pn-junction becomes nearly zero under a reverse bias condition. As a result, the electric field is greatly reduced and a significantly improved breakdown voltage can be expected.

Fig. 2(a) and 2(b) show the electric field distribution of the conventional and proposed device structures along the GaN surface (x-x' line) and buffer (z-z' line) as illustrated in Fig 1, where the drift region extension L_{drift} is 20 μm under a reverse bias of 600 V. It can be seen that a peak electric field existing at the edge of the anode (at 10 μm of X-axis) in the conventional structure. The simulation results clearly indicate that the proposed structure employing the buried pn-junction can significantly reduce the peak electric field at the Schottky contact edge owing to the charge balance effect. Moreover, it is known that the breakdown event may also occur in the GaN or AlN buffer layer. The buried pn-junction can redistribute the electric field in the buffer layer leading to a smooth electric field profile without any obvious peaks as shown in Fig 2 (b). Fig. 3 shows the electric field distribution along the pn-junction boundary (y-y' line) with various drift length from 10 to 50 μm under reverse bias 600V condition for the barried p-layer structure. It can be seen that the peak electric field is effectively reduced as L_{drift} keeps increasing along the pn-junction. In contrast, the peak electric field of the conventional structure is almost constant even with a large L_{drift}.

For the proposed structure, the simulated breakdown voltage V_{BK} defined by a peak electric field approaching the critical breakdown field (3MV/cm) is shown in Fig. 4 with different L_{drift} from 10 μm to 40 μm. The breakdown voltage increases linearly by increasing the drift length. An excellent breakdown voltage up to 4800 V can be obtained with an L_{Drift} of 40 μm. An even higher V_{BK} is possible if a larger L_{Drift} is employed. On the other hand, the breakdown voltage of the conventional device is limited at around 130 V even when the drift length is increased to 40 μm, as also shown in the figure.

One critical issue of using the charge balance method is that the doping concentrations of both the n-type and p-type GaN layers should be controlled precisely. Fig 5 shows the V_{BK} variation as a function of the charge imbalance percentage (defined as (P-N)/N×100%). The breakdown voltage degrades more obviously as the charge imbalance percentage and doping concentration increase. The charge imbalance issue may not be completely avoided in practical material growth, while a relatively low doping concentration and a large L_{drfit} can be used to alleviate the effect of charge imbalance.

3. Conclusion

In this study, we proposed a new structure for GaN Schottky diodes on Si substrate. By employing the buried pn junction with the charge compensation concept, the electric filed was redistributed and the peaks around the metal contacts were reduced significantly. The simulated result demonstrated that the breakdown voltage can be improved from 130 V of the conventional device up to the 4800 V.

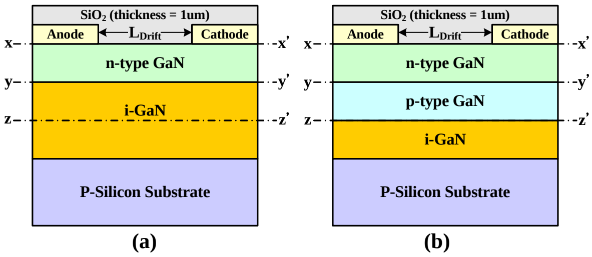

Fig. 1. Cross section view of (a) conventional GaN Schottky diode device structure (b) proposed structure with a buried pn-junction.

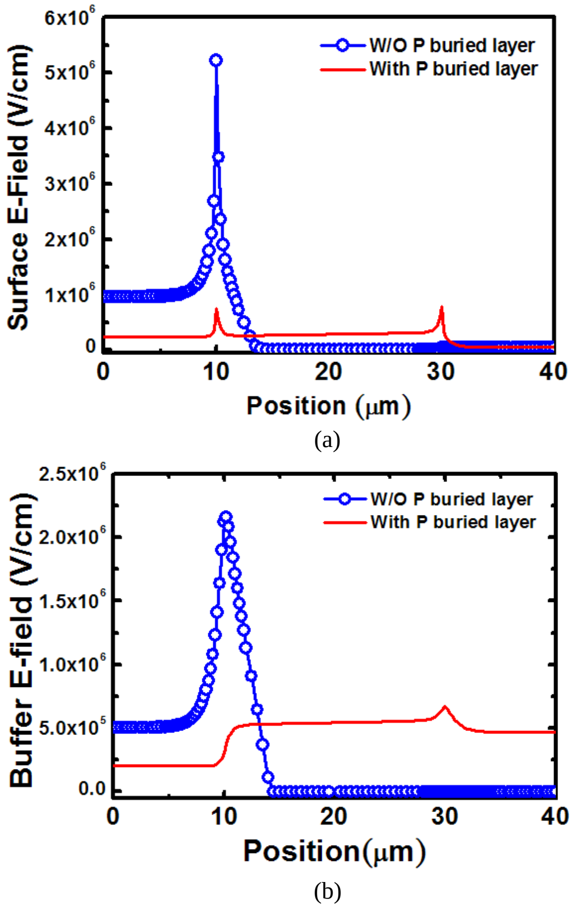

Fig. 2. Electric field distribution along (a) the surface (x-x' line) and (b) the buffer (z-z' line) of the devices with and without the p-buried layer.

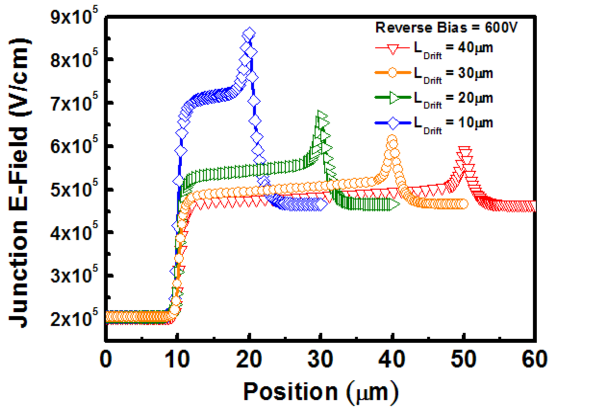

Fig. 3. Electric field distribution with p-buried layer along the y-y' line with various L_{Drift} under a reverse bias of 600 V.

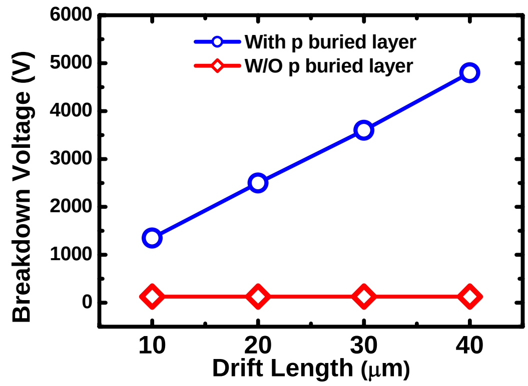

Fig. 4. Reverse breakdown voltage of a Schottky diode with (N = P = $5x10^{16}/cm^3$) and without p (N = $5x10^{16}/cm^3$) buried layer as a function of L_{Drift}.

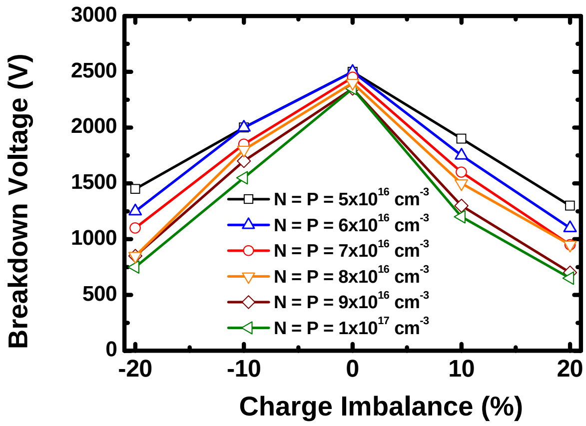

Fig. 5. The breakdown voltages versus different charge imbalance percentages with different doping concentrations.

References

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