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Breaking the GaN Material Limits with Nanoscale Vertical Polarisation Super Junction Structures – A Simulation Analysis

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Abstract

This is the first report on the performance of nanoscale vertical superjunction structures based on impurity doping and introduces an innovative approach that utilizes the polarisation properties inherent in III-V nitride semiconductors. Such nanoscale vertical polarisation super junction structures can be realized by employing a combination of epitaxial growth along the non-polar crystallographic axes of Wurtzite GaN and nanolithography techniques. Detailed simulations clearly highlight the limitations of a doping based approach and the advantages of the proposed solution for breaking the 1-D material limits of GaN by orders of magnitude.

1. Introduction

Gallium Nitride (GaN) power semiconductor devices are emerging as chosen candidates for the next generation of power electronics due to its superior intrinsic material properties in comparison to Silicon (Si). Present GaN power devices are of lateral topology and use high density of electrons arising due to its polarisation properties. However, with the commercial availability of large area bulk GaN substrates with low dislocation density, development activities towards vertical devices are gaining substantial traction [1-3]. Advantages of a vertical architecture include ease of voltage scalability, avalanche capability, enhanced reliability and reduction in area-specific on-state resistance (R_{ON}.A). However, the cost-performance ratio is limited for conventional GaN devices as bulk GaN substrates remain expensive, and offer marginal gains over 4H-Silicon Carbide (SiC), which is a more mature wide bandgap device technology.

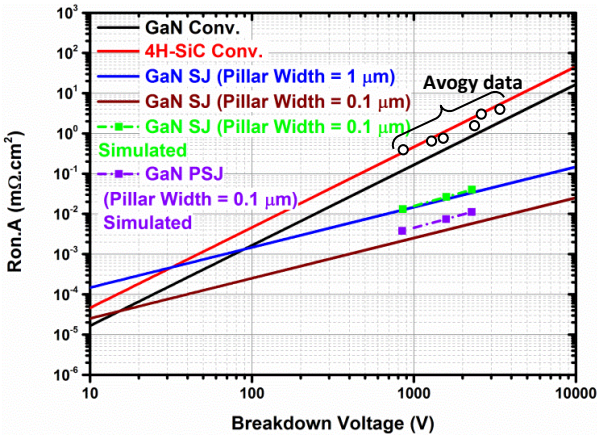

Fig. 1 Specific on-state resistance vs. breakdown voltage

Fig.1 shows the theoretical material limits for conventional (GaN and 4H-SiC) and superjunction (SJ) structures, reported data on vertical GaN devices from Avogy, Inc. as well as simulation results from this study. SJ structures in Si operate on the principle of charge compensation in precisely doped alternating p-type and n-type columns, and have enabled performance beyond its material limit [4]. By adopting such SJ architecture, the performance of bulk GaN based devices can improve by orders of magnitude in comparison to 4H-SiC; however, dopant based approach in GaN is very immature and is unrealistic due to difficulties of controlled Mg activation. On the other hand, polarisation based superjunction has been demonstrated in lateral GaN devices using polarisation engineering [5]. However, this scenario is likely to change with the availability of polar and non-polar bulk GaN substrates and the advances made in the growth of high aspect ratio GaN nano-columns [6-7]. This pioneering article presents the performance analysis of vertical power GaN devices based on conventional SJ and polarisation super junction (PSJ) concepts.

2. Vertical Polarisation Super Junction

Fig. 2 shows the schematic of a conceptual GaN-AlGaN-GaN PSJ structure grown along a non-polar axis (perpendicular to the polar c-axis).

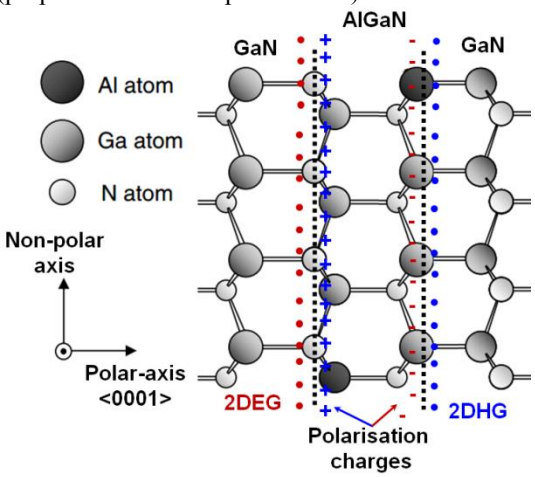

Fig. 2 Schematic illustration of atomic arrangement in a vertical GaN-AlGaN-GaN PSJ structure

It also illustrates the inherent compensation of polarisation charges and accumulation of high mobility charge carriers (two-dimensional electron gas (2DEG)/two-dimensional hole gas (2DHG)). As in a lateral PSJ device, the on-state conduction can take place primarily using the 2DEG which is both doping and temperature independent. During

off-state, the polarisation charges along the GaN(0001)/AlGaN(000$\bar{1}$) and AlGaN(0001)/GaN(000$\bar{1}$) vertical interfaces compensate each other, enabling a uniform 'box' like electric field distribution. This maximizes the breakdown voltage for a given drift thickness [5].

3. Numerical Simulation

Numerical two-dimensional simulations were performed using Silvaco ATLAS. The following models were included: FERMI, SRH, SELB, FMCT.P and FMCT.N. An optimal charge density of $1x10^{13}$ cm^{-2} is assumed for both the doped and PSJ structures. For a doped SJ structure, the doping density in the p and n columns was set as $2.05\ x10^{17}$ cm^{-3} and $2.05\ x10^{18}$ cm^{-3} for pillar widths of 1 µm and 0.1 µm respectively [8]. For the PSJ structures, interface charge density of $+1x10^{13}$ cm^{-2} and $-1x10^{13}$ cm^{-2} was defined at the alternating interfaces. The simulated structures (Schottky Barrier Diodes) have been shown in Figs. 3 (a)-(b).

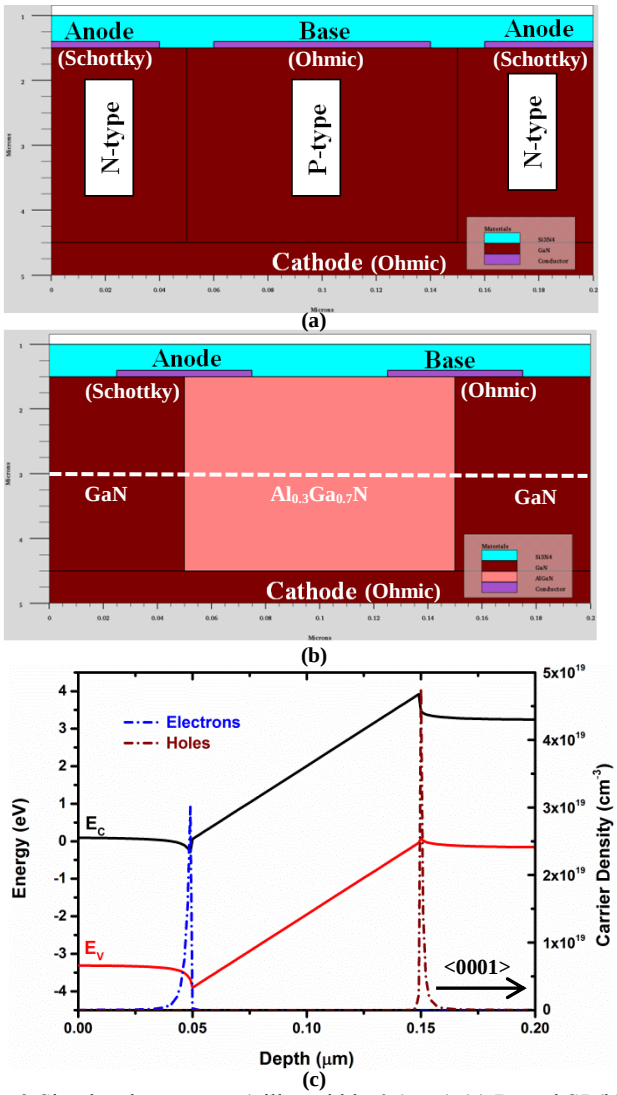

Fig. 3 Simulated structures (pillar-width=0.1 µm) (a) Doped SJ (b) PSJ (c) Energy Band Diagram (along the dashed line, equilibrium)

Forward I-V characteristics and electric field profile (uniform distribution) within the structures at various reverse bias conditions have been shown in Figs. 4-5 respectively.

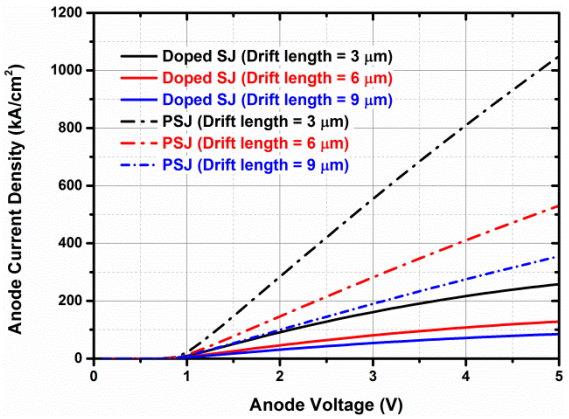

Fig. 4 Forward I-V characteristics (pillar-width=0.1 µm)

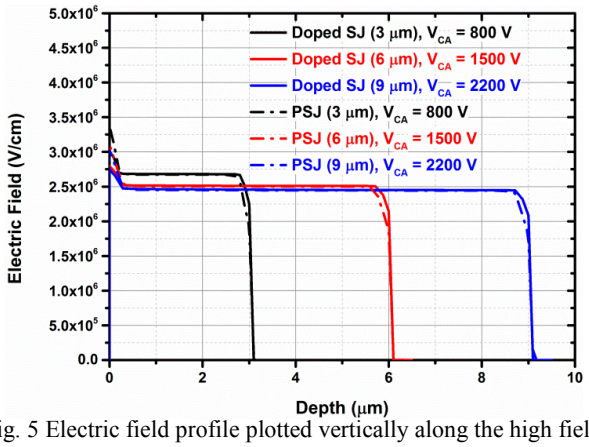

Fig. 5 Electric field profile plotted vertically along the high field drift region (Anode to Cathode), at various reverse bias conditions

4. Concluding Remarks

GaN SJ structures with a pillar-width of 0.1 µm require doping concentration in the range of 10^{18} cm^{-3} which makes p-type doping challenging. The increased doping density also deteriorates electron mobility. This in combination with lateral depletion even under thermal equilibrium (causes ineffective utilization of the active area) leads to sub-optimal performance of such structures. PSJ structures overcome the above-mentioned challenges as on-state conduction takes place using high density/mobility 2DEG, maintaining charge balance under off-state conditions. As shown in Fig. 1, compared to material limits, a reduction of almost two orders of magnitude in $R_{ON}.A$ can be achieved using PSJ structures for breakdown voltage of 1kV, which could extend to three orders of magnitude improvement for 10kV devices, in comparison to 4H-SiC. In conclusion, polarisation engineering as proposed in this article is an effective solution to bring forward ultra-high efficient power devices for energy savings.

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