Design and Manufacture of Edge Termination in Vertical GaN Diodes: Electric Field Distribution Probed by Second Harmonic Generation

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Keywords: GaN, vertical diodes, edge termination, SHG, electric field

Abstract

Device design and manufacturing of power devices requires edge termination to manage peak electric fields, but validation of its effectiveness is presently rather indirect. We characterized the electric field distribution of GaN p-n diodes with ion-implanted two-step bevel edge termination using an electric field induced second harmonic generation technique (EFISHG). Though breakdown voltage of 800V measured, which is sufficient for numerous applications, we demonstrate EFISHG analysis can be used to improve this even further. The measured electric field distribution shows that the net acceptor concentration in the edge termination region was not fully optimal, providing feedback for improved device development and manufacturing.

INTRODUCTION

GaN-based power electronics have attracted much attention for power conversion applications due to GaN's superior critical electric field and electron mobility. Recently, the emergence of high-quality bulk substrates have resulted in the demonstration of vertical GaN power diodes with high breakdown voltages [1]. A key issue for GaN vertical power devices is the edge termination (ET) structure for mitigating electric field crowding at the junction edge [2]. There are different edge termination types reported for GaN devices, such as moat termination [3], junction termination extension (JTE) [4] and bevel termination [5]. Breakdown voltage (BV) is usually the only criteria to evaluate the effectiveness of the ET but cannot deliver direct information about internal characteristics and structure optimization of ET.

In this study, we applied the electric field induced second harmonic generation (EFISHG) [6] technique to measure the electric field distribution of a GaN p-n diode with an ion-implanted two-step bevel edge termination. The measured electric field distribution indicates that the net acceptor concentration in the edge termination is not optimal, and that a higher Mg ion implantation dose is required to fully compensate the donor-type damage induced by dry etching.

DEVICE STRUCTURE

Fig. 1a shows the structure of the GaN p-n diode with ion-implanted two-step bevel edge termination with a similar fabrication process as [3]. The epitaxy layers consist of a 12-µm-thick n$^-$GaN with Si doping concentration of 1.5×10^{16} cm^{-3}. The net doping concentration of the drift layer was analyzed by capacitance-voltage measurement. Above the n$^-$GaN layer is a 450-nm-thick p$^+$GaN layer with Mg concentration of 1×10^{19} cm^{-3} which was determined by secondary ion mass spectroscopy (SIMS) A 50-nm-thick p^{++}GaN layer is used to facilitate the Ni/Au ohmic contact.

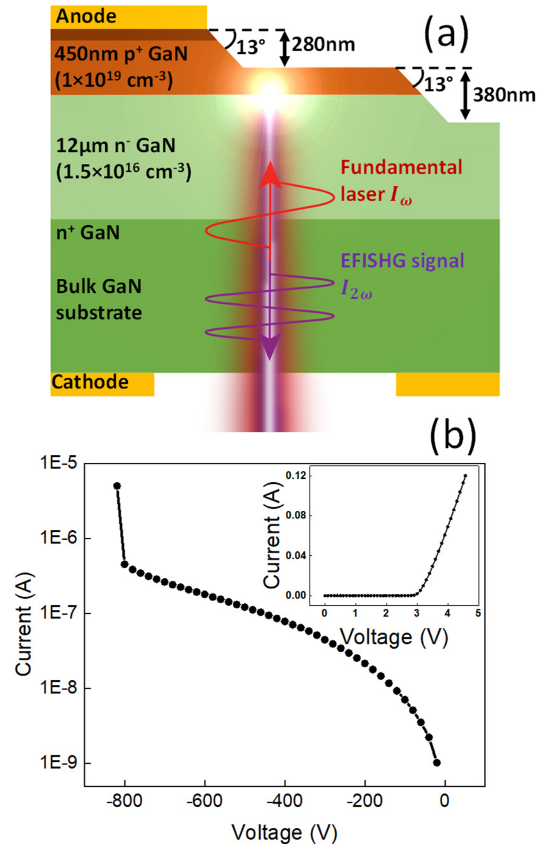

Fig.1 (a) Schematic of the GaN p-n diode and backside EFISHG measurement. (b) *IV* characteristics showing a breakdown voltage of 800V and turn-on voltage of 3V.

The edge termination structure was prepared by reactive ion etching (RIE). The edge termination consists of a partially thinned p-GaN layer with an inner bevel around the anode and outer bevel etched into the n$^-$GaN drift layer. The lateral extent of the edge termination is designed to be 22 µm. A titled Mg ion implantation with a thick metal mask was adopted to compensate the donor-type damages induced by plasma-based dry etch [7]. Transport of ions in matter (TRIM) was used to model the implant profile which is a standard gaussian distribution with the peak concentration around the p-n

junction. Fig. 1b shows the *IV* characteristics of the device with ion implantation dose of 5×10^{13} cm^{-2} and BV of 800V. One option for enhancing breakdown voltage may be increasing the ion implantation dose to 5×10^{14} cm^{-2} [3].

ELECTRIC FIELD MEASUREMENT

EFISHG has been confirmed to be an effective technique for quantitative electric field measurement in GaN HEMT [6]. By focusing a fundamental laser into the channel inside the device, a second harmonic generation (SHG) signal can be generated and detected. The intensity of the SHG signal is dependent on the local electric field strength and can be used to determine the electric field distribution in channel. Fig. 1a shows the schematic of the EFISHG measurement, with more details of the technique given in [6].

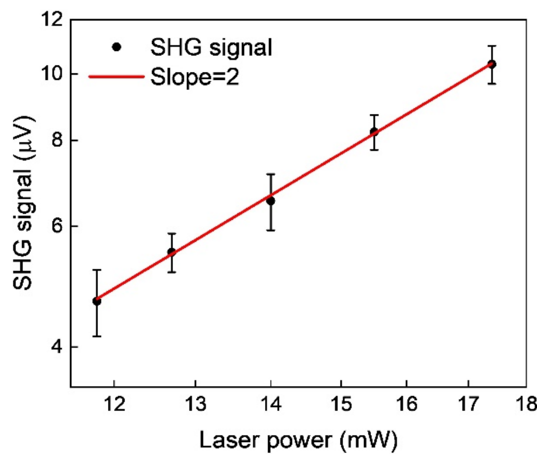

Fig. 2 SHG signal measured as function of incident laser power showing a quadratic dependence.

Fig. 2 shows the quadratic dependence of the detected signal on incident laser power demonstrating the SHG nature of the signal. As shown in Fig. 1a, a fundamental laser beam with wavelength of 800nm was focused onto the sample in a normal-incidence geometry and the SHG at 400nm, below the bandgap of the GaN, is detected. Due to the off-axis reflection of bevels, the SHG signal around bevels cannot be collected by the system. The field crowding happens around the bevels with peak fields of both lateral and vertical electric field, while the field under the anode and partially thinned p-GaN layer is mainly vertical field from p-n junction. Thus, the detected EFISHG signal is mainly determined by vertical electric field E_z under the anode and the partially thinned p-GaN layer. A 400nm laser is used to normalize the different reflectance of the SHG signal under anode and partially thinned p-GaN layer. A more accurate electric field distribution can be extracted from SHG signal after reflectance calibration. The electric field can then be determined using $E_z \propto \sqrt{I_{2\omega}\text{-}I_{2\omega}(E_z\text{=}0)}$, where $I_{2\omega}$ is the total SHG signal and $I_{2\omega}(E_z\text{=}0)$ is the fundamental SHG signal without an applied field (i.e., zero bias).

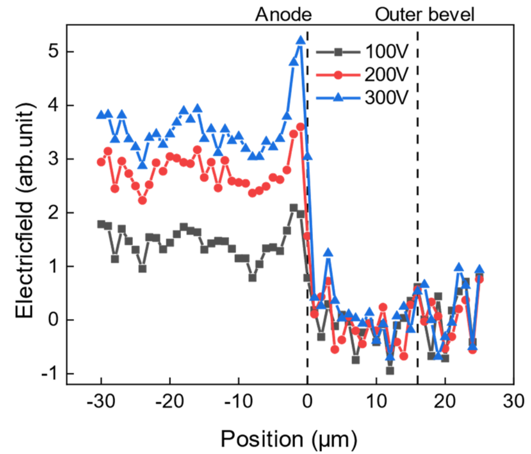

Fig. 3 Electric field distribution between anode and outer bevel of the edge termination in investigated GaN p-n diode.

RESULTS AND DISCUSSIONS

Fig. 3 shows the EFISHG-extracted electric field distribution under reverse bias conditions. EFISHG measurement was performed along the radial line between anode and outer bevel of the edge termination. The electric field is only present under the anode with a peak around the edge of the anode. No electric field has been detected in partially thinned p-GaN region. The electric field distribution was simulated using Silvaco ATLAS to investigate how the edge termination affects the electric field distribution. Fig.4 shows simulated electric field contours (a, b, c) and E_z distribution (d) along the p-n junction under 300V reverse bias. Different edge termination schemes were simulated: moat edge termination (Fig. 4a); JTE and bevel edge termination with full (Fig. 4b) and partial (Fig. 4c) activation of Mg in p-GaN. These three cases reflect different relative values of ion implantation dose and donor-type damage density but show similar breakdown voltage around 800V.

When considering a high ion implantation dose compared to the concentration of donor-like damages, the edge termination is similar to the moat etch termination concept [3]. In Fig. 4a, the surface region of the drift layer becomes p-type due to the Mg ion implantation. The main p-n junction extends to the outer bevel with the electric field terminated by p-GaN in the surface of the drift layer. However, a uniform electric field distribution along the whole junction even outside the second bevel (Fig.4d) was not observed here experimentally.

For a low ion implantation dose (Fig. 4b) compared to the concentration of donor-like damages, the remaining donor-type damages cause the reduction of the net acceptor concentration in partially thinned p-GaN layer. This causes the spread of the electric field within the JTE formed by a partially thinned p-GaN layer. The peak electric field has been pushed into the bulk from the surface because of the bevel structure. However, the extracted vertical electric field shows uniform field distribution from anode to the end of the outer bevel (Fig.4d) which is inconsistent to experimental results.

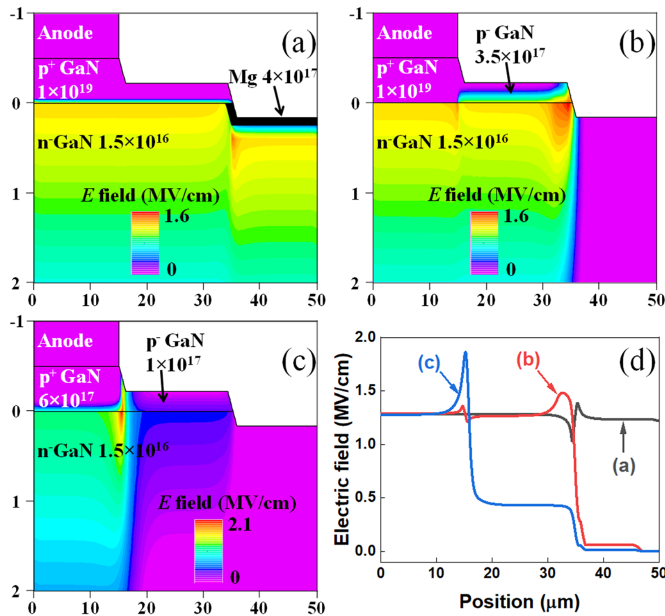

Fig.4 Simulated electric field contour (a, b, c) and E_z profile along the p-n junction (d) under 300V reverse bias.

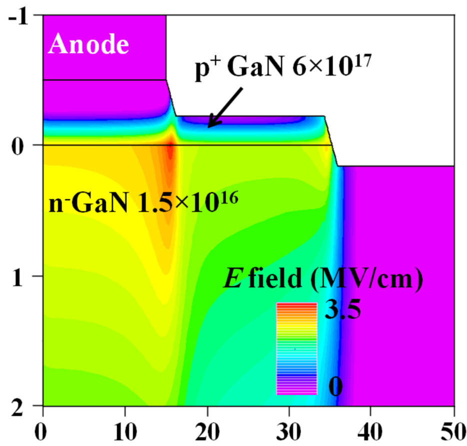

Fig.5 Simulated electric field contour under 1.4kV reverse bias with full compensation of donor-like damages in partially thinned p-GaN.

The experimental results agree most with third scenario. Partial activation of Mg in p-GaN is assumed in this case which has been reported due to the compensation of donor sources incorporated during the growth of the p-type GaN layer [8, 9]. Further reduction of net acceptor concentration in etched region due to uncompensated donor damages leads to early depletion of the partially thinned p-GaN layer (Fig.4c); a vertical electric field distribution similar to the measurement (Fig.4d) is obtained. This electric field distribution demonstrates the underlying mechanism of this edge termination design and indicates the low activation ratio of Mg in p-GaN. The ET mitigates the field crowding by taking advantage of the JTE formed by the partially thinned p-GaN layer and bevels. However, the low net acceptor concentration in JTE limits the effectiveness of the ET and results in the BV around 800V. Full compensation of donor-like damages in the partially thinned p-GaN leads to a BV of 1.4kV (Fig.5) in simulation, which matches the optimal BV [3], i.e., when the device investigated here was fully optimized. This indicates a higher implanted Mg dose is needed to maximize the potential of ET.

Conclusion

EFISHG was used to characterize the electric field distribution of a GaN p-n diode with ion implanted two-step bevel edge termination. The measured electric field distribution clearly confirms the edge termination scheme and demonstrates the low net acceptor concentration in the edge termination region, which limits the effectiveness of the edge termination. This is consistent with the high breakdown voltage measured for the fully optimized device. This direct electric field measurement technique uniquely aids structure optimization and manufacturing validation.

Acknowledgement

Research at the University of Bristol was supported as part of ULTRA, an Energy Frontier Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), under Award # DE-SC0021230 and by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/R022739/1. Y. Cao acknowledges the China Scholarship Council for financial support under grant 201806290005.

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ACRONYMS

EFISHG: Electric field induced second harmonic generation
JTE: Junction termination extension
BV: Breakdown voltage
ET: edge termination
RIE: Reactive ion etching
SHG: Second Harmonic Generation
TRIM: Transport of ions in matter