SAND2019-10817C

Bevel Edge Termination for Vertical GaN Power Diodes

Andrew T. Binder*, Jeramy R. Dickerson, Mary H. Crawford, Greg W. Pickrell, Andrew A. Allerman, Paul Sharps, Robert J. Kaplar

Sandia National Laboratories, Albuquerque, NM 87185, USA

*abinder@sandia.gov

***Abstract*—Edge termination for vertical power devices presents a significant challenge, as improper termination can result in devices with a breakdown voltage significantly less than the ideal infinite-planar case. Edge termination for vertical GaN devices is particularly challenging due to limitations in ion implantation for GaN, and as such this work investigates a bevel edge termination technique that does not require implantation and has proven to be effective for Si and SiC power devices. However, due to key differences between GaN versus Si and SiC p-n junctions (specifically, a grown versus an implanted junction), this technology needs to be reevaluated for GaN. Simulation results suggest that by leveraging the effective bevel angle relationship, a 10-15° physical bevel angle can yield devices with 85-90% of the ideal breakdown voltage. Results are presented for a negative bevel edge termination on an ideally 2 kV vertical GaN p-n diode.**

***Keywords*—vertical GaN diode; edge termination; junction termination extension; power devices**

I. Introduction

Optimization of breakdown in vertical power devices is often limited by field crowding at the periphery of the device. For an ideal planar device, the breakdown is limited by the peak electric field in the bulk, yielding a much higher breakdown voltage than for a device limited by a large surface electric field. To address this issue, special junction terminations around the edges of the power device can be formed so that the depletion near the surface is increased, thereby reducing field crowding. The most common edge termination structures in Si and SiC (junction termination extensions {JTEs} and guard rings) are created by selective-area doping using ion implantation. However, Mg implantation in GaN aimed at achieving selective-area p-type doping suffers from low activation efficiency and a limited effective range of implantation energy and dose [1], making this method challenging to use in GaN power devices. An alternate junction termination method that does not require selective-area doping is the negative bevel edge termination which has been demonstrated both in Si and SiC power devices [2], [3]. However, epitaxially-grown p-n junctions in GaN are much more abrupt than implanted junctions in Si and SiC power devices [4], [5], resulting in important differences in how these regions deplete, impacting the effectiveness of a bevel termination.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

In this work, a vertical GaN p-n diode is used to evaluate the performance of a negative bevel edge termination. It should be noted that this edge termination technique is not in any way limited to this particular device, but can be applied to a wide range of devices.

II. Theoretical Background

A. Single-Zone/Multi-Zone JTE

The design of a single-zone or multi-zone JTE hinges on Gauss's law and the charge enclosed in the Gaussian surface (the JTE) [6], [7]. According to Gauss's law, the electric flux through any closed surface is equal to the total charge inside divided by the permittivity as shown in Eq. 1:

$$\phi = E \cdot A = \frac{\sigma \cdot A}{\varepsilon_r \cdot \varepsilon_0} \tag{1}$$

where ϕ is the electric flux, σ is the charge per unit area, ε is the permittivity, A is the area of the Gaussian surface, and E is the electric field.

In this manner, the charge inside the JTE acts as a sink for the electric field in a power device at breakdown, causing the field lines to terminate into the JTE and not crowd at the periphery of the device. Premature breakdown occurs in unterminated devices when field crowding at the periphery of the device causes the surface E-field to exceed the bulk E-field by a significant margin. In properly terminated devices, at breakdown the E-field at the surface will be equal to the E-field in the bulk thereby maximizing the breakdown voltage of the device. An ideal termination is obtained when the charge in the JTE is designed to sink the critical electric field (E_{crit}).

The disadvantage of a single-zone JTE (SZ-JTE) is that the JTE efficiency (the ratio of the breakdown voltage in a terminated device to the breakdown voltage of an ideal one-dimensional device) is very sensitive to changes in total charge within the Gaussian surface, and therefore sensitive to the thickness and doping density of the JTE [8], [9]. One method to reduce this sensitivity to process variation is to design a multi-zone JTE (MZ-JTE) which employs several JTEs each with a unique total JTE charge [9]. However, each additional zone requires additional fabrication steps, further complicating the process. In addition, both the SZ-JTE and MZ-JTE suffer from adverse effects of surface charge that strongly depend on passivation, which needs careful consideration when designing for the optimal total JTE charge. Surface charge resulting from passivation can effectively reduce voltage-blocking capability by 25-50% depending on the net interface state density [10].

B. Bevel Edge Termination

The analog approach to a step change in charge across multiple regions (MZ-JTE) is to create a bevel with a continuum of charge. With a bevel, the charge in the Gaussian surface is not a discrete value that can be hit or missed due to process variation, but rather is a continuous range which is less sensitive to changes in total JTE charge. In direct contrast to the SZ/MZ-JTE, the effectiveness of the bevel edge termination is also insensitive to surface charge, due to the continuum of charge in the bevel.

The design for a bevel edge termination is primarily based on two factors: the ratio of the depletion depth into the JTE to the depletion into the drift region, and the angle of the bevel. A negative bevel with a small bevel angle can be used to reduce the peak surface electric field by increasing the depletion width on the surface relative to the depletion width in the bulk as shown in Fig. 1. The increased surface depletion in turn reduces the E-field at the surface, given that a constant voltage across a greater depletion width yields a smaller E-field ($E = dv/dx$). When the bevel angle is sufficiently small the E-field at the surface will be equal to or less than the E-field in the bulk, yielding near-ideal breakdown performance in the terminated device.

C. Effective Bevel Angle

For a beveled device, the edge termination becomes more effective for the same bevel angle when the depletion depth into the bevel (x_p) increases (see Fig. 1) [11], [12]. This relationship can be expressed in terms of an effective bevel angle.

One fundamental difference between junctions in GaN versus junctions in SiC or Si devices is that generally GaN junctions are grown and are therefore much more abrupt than SiC junctions, which are implanted or diffused. This fundamental difference has a significant impact on the effective bevel equation. As Adler *et al.* [11] demonstrate in their early paper, for a diffused junction the effective bevel angle is a function of the ratio of the depletions widths squared (Eq. 2), but for an abrupt junction it is simply the ratio of the depletion widths (Eq. 3):

$$Diffused\ Junction: \quad \theta_{eff} = 0.04 \cdot \theta_{act} \cdot \left(\frac{x_{DB}^{-}}{x_{DB}^{+}}\right)^{2} \quad (2)$$

$$Abrupt\ Junction: \quad \theta_{eff} = 0.04 \cdot \theta_{act} \cdot \left(\frac{x_{DB}^{-}}{x_{DB}^{+}}\right) \quad (3)$$

where θ_{act} is the physical bevel angle, x_{DB}^{-} is the depletion width into the lightly-doped side at breakdown (i.e. x_n), and x_{DB}^{+} is the depletion width into the heavily-doped side at breakdown (i.e. x_p).

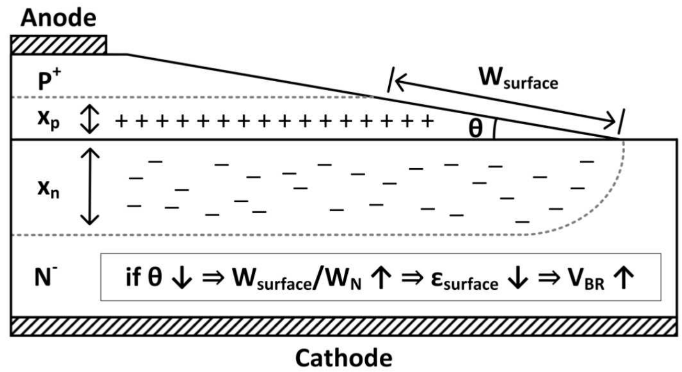

Fig. 1. Representation of fundamental theory for a negative bevel edge termination.

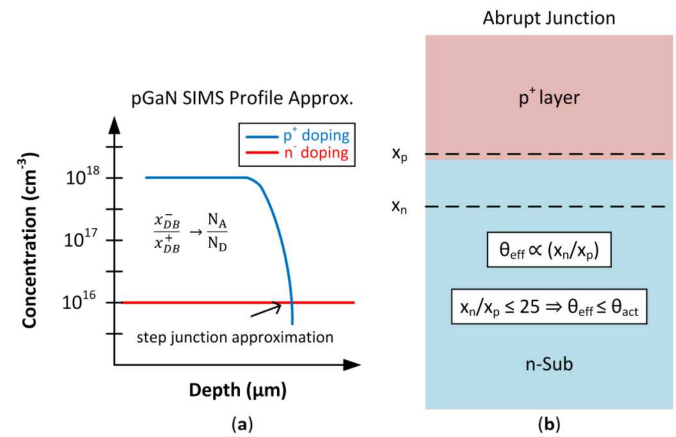

Fig. 2. Simplified representation of (a) the doping profile for an epitaxially grown p-n junction in GaN, and (b) an example of an abrupt junction and the associated bevel angle relationships.

Accordingly, an abrupt junction profile can be more easily leveraged to produce an effective bevel angle that is smaller than the physical bevel angle, making GaN an inherently better candidate for a bevel edge termination compared to Si or SiC. For an epitaxially-grown GaN p-n junction the doping profile approximates a step junction as depicted in Fig. 2(a). In the case of a step junction the ratio of the depletion widths is equal to the inverse of the ratio of the doping density in the two regions (Eq. 4).

$$\frac{x_n}{x_p} = \frac{N_A}{N_D} \quad (4)$$

The effective bevel angle equation acts as a normalization factor to evaluate the impact of bevel angle considering variation in doping on either side of the junction. In practice, however, it is also possible to use this equation to leverage the physical bevel angle by manipulating the doping such that the effective bevel angle is smaller than the physical bevel angle. This results in high breakdown performance but with a larger bevel angle, thus increasing the manufacturability of such a structure. The effective bevel angle will be smaller than the

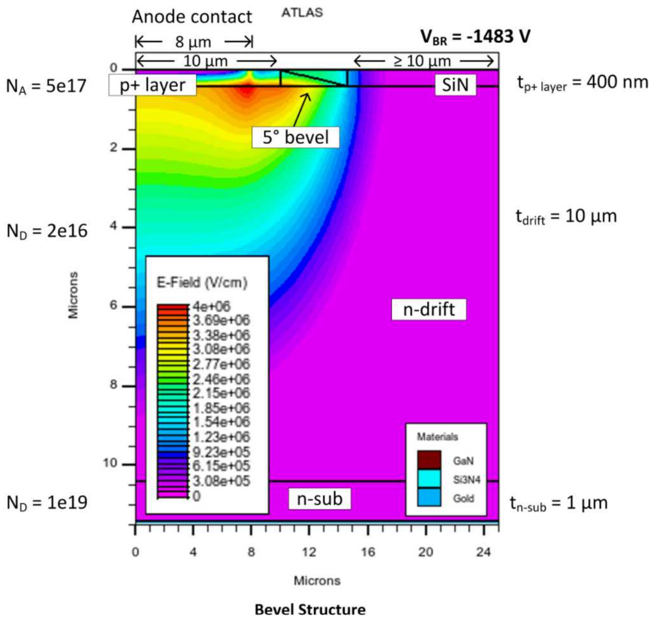

Fig. 3. Baseline simulation structure used to evaluate the negative bevel edge termination.

TABLE 1
SIMULATION PARAMETERS AND VALUES

Symbol	Quantity	Value
E_g	GaN Bandgap	3.44 eV
E_{crit}	Critical Electric Field	4 MV/cm
ε_s	Relative Permittivity	9.7
T	Temperature	300 K
μ_p	Hole Mobility	11 cm²/Vs
μ_n	Electron Mobility	1200 cm²/Vs

physical angle when $x_n/x_p \leq 25$ resulting from the relationship shown in Eq. 3. This can be achieved by increasing the thickness of the p-GaN layer and lowering the doping to increase the depletion depth into the p-layer. The study of an effective bevel design for a vertical GaN device is presented in the following sections.

III. Device Design and Simulation Model

To evaluate the impact of a bevel edge termination on a vertical GaN power diode, we evaluate breakdown performance focusing specifically on the influence of bevel angle, p-GaN doping concentration, and p-GaN thickness. These results are compared to the ideal one-dimensional device breakdown to yield a performance figure that is the ratio of the breakdown voltage in the terminated device to the ideal breakdown voltage ($V_{B(beveled)}/V_{B(planar)}$), also referred to as the JTE efficiency.

The device under study is nominally a 2 kV p-n junction power diode with a drift thickness and doping of 10 µm and 2 × 10^{16} cm^{-3} respectively. The baseline simulation structure used for evaluation is shown in Fig. 3 with all listed parameters held constant with the exception of bevel angle, p-layer doping, and p-layer thickness.

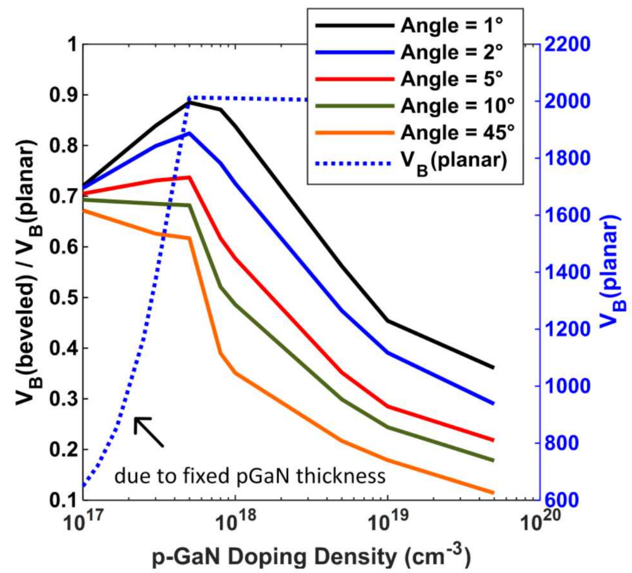

Fig. 4. Normalized breakdown voltage versus p-GaN doping density for varying bevel angles at t_{pGaN} = 400 nm (left y-axis), and ideal breakdown voltage versus p-GaN doping (right y-axis).

Device simulations were performed with Silvaco TCAD [13] to determine the reverse-bias avalanche breakdown voltage. Breakdown for the simulation is defined as the point at which the reverse-bias current density reaches 10 mA/mm², indicating the onset of avalanche. Impact ionization coefficients were specified such that at a drift doping of 2 × 10^{16} cm^{-3} the critical electric field (E_{crit}) is 4 MV/cm [14] which determines the point at which breakdown occurs. Further simulation parameters are given in Table 1 and were developed previously in [15] and [16] for similar vertical-GaN-based simulation work.

IV. Results and Discussion

For a fixed drift layer design (fixed drift layer thickness and doping) the design of the bevel is dependent on three parameters: bevel p-layer thickness, p-layer doping, and bevel angle. The design considerations for bevel thickness and p-layer doping should be linked, with the desired design outcome being to maximize the depletion depth of the bevel, which serves to leverage the effective bevel angle relationship. By increasing the depletion depth into the bevel, the physical bevel angle can be increased while still yielding the same breakdown performance. This is very desirable considering that shallow (< 10°) bevel angles can not only consume a considerable amount of wafer area but are quite difficult to manufacture.

Normalized breakdown voltage versus p-layer doping is shown in Fig. 4 for a fixed p-GaN thickness of 400 nm. In addition, the breakdown voltage for the ideal device is shown on the right axis for comparison. Notice that for $N_A \leq 5 \times 10^{17}$ cm^{-3} the ideal breakdown voltage drops sharply. This is an example of what happens when the p-region under the anode contact fully depletes and can be corrected simply by increasing the p-GaN thickness or doping so that the layer does not fully deplete. From this figure it is seen that at $N_A = 5 \times 10^{17}$ cm^{-3} a bevel angle of 1° approaches 90% of the ideal breakdown voltage, but a 5° bevel is only 75% ideal. It is important to note

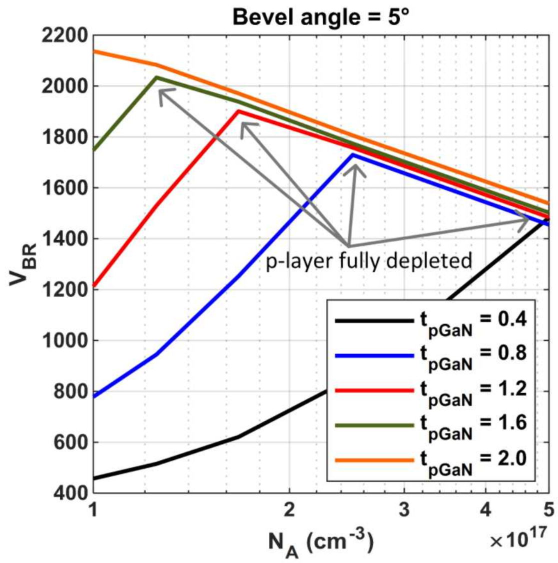

Fig. 6. Breakdown voltage versus p-GaN doping density for varying p-GaN thickness (in µm).

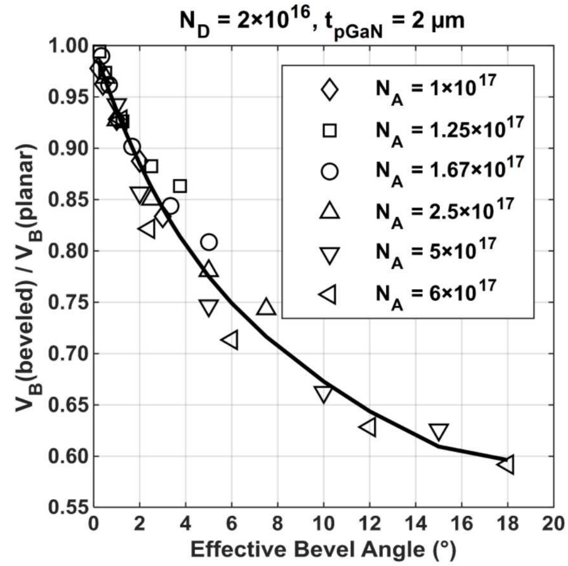

Fig. 7. Effective bevel angle plot normalizes the bevel angle to account for variations in doping.

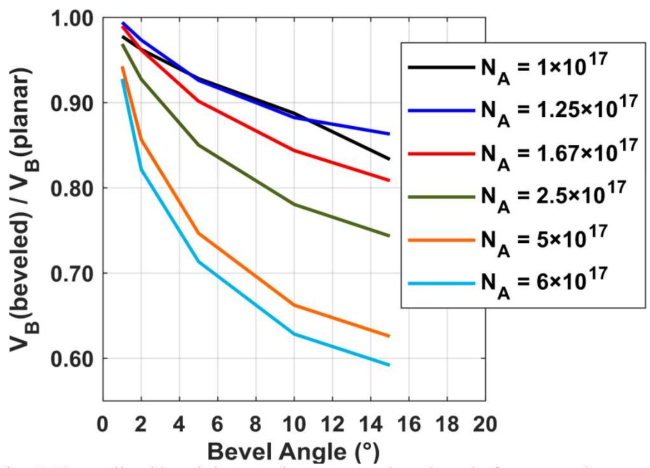

Fig. 5. Normalized breakdown voltage versus bevel angle for t_{pGaN} = 2 µm.

that for these doping levels, the effective bevel angle is equal to the physical angle, with the drift doping set to 2 × 10^{16} cm^{-3} and the p-layer doping at 5 × 10^{17} cm^{-3} (see Eq. 3). This means that the effective bevel angle relationship is completely unleveraged.

To leverage the effective bevel angle relationship, the p-layer doping should be reduced below 5 × 10^{17} cm^{-3} for the given drift doping. Since the depletion depth into the p-layer is directly proportional to the doping concentration, reducing the doping by a factor of five requires a p-layer that is five times thicker. As mentioned previously, while a single-zone JTE is very sensitive to both doping density and thickness of the JTE, a bevel edge termination does not require precise control of these variables to achieve good breakdown performance. This is highlighted in Fig. 5 which shows similar expected breakdown voltage as the p-layer thickness is varied, and an overall increase in breakdown voltage as the doping is reduced so long as the doping is not reduced to the point that the layer under the anode contact fully depletes.

Given that a much thicker p-layer is needed to accommodate doping down to 1 × 10^{17} cm^{-3}, Fig. 6 shows the impact on breakdown performance of bevel angles less than 15° given t_{pGaN} = 2 µm. Note that as the bevel approaches the fully depleted scenario (at 1 × 10^{17} cm^{-3}) the increase in breakdown performance begins to saturate, with results for 1-1.25 × 10^{17} cm^{-3} yielding similar breakdown performance. However, at this doping level (1-1.25 × 10^{17} cm^{-3}) it is possible to achieve nearly 90% of the ideal breakdown voltage for a bevel angle of 10°. This is a considerable improvement over the 1° bevel angle necessary to approach 90% ideality at $N_A = 5 \times 10^{17}$ cm^{-3}.

The data from Fig. 6 can be reduced to a single function by normalizing the data using the effective bevel relationship in Eq. 3. This normalization accounts for variation in doping and demonstrates a very good fit, showcasing the accuracy of the analytical equation for an abrupt junction (Eq. 3). This normalized data is presented in Fig. 7 demonstrate that for an effective bevel angle of less than 1° it is possible to reach near 100% ideality for breakdown performance. The symbols in Fig. 7 represent the discrete datapoints from the simulations represented in Fig. 6 normalized using Eq. 3.

To obtain such a high level of breakdown performance, it is necessary to significantly leverage the effective bevel angle equation by using a very low-doped and consequently very thick p-layer, or by fabricating very shallow bevel angles. Fabricating a very thick p-layer with low doping is generally undesirable due to the negative impact on forward resistance (R_{on}). However, by employing a moderate approach with respect to p-layer doping and thickness, it is possible to take advantage of the effective bevel relationship without significantly increasing R_{on}.

V. Conclusion

The bevel edge termination is fundamentally a very attractive approach to realizing the full breakdown performance for a vertical power device. In contrast to a single/multi-zone JTE, the bevel design is robust to changes in p-layer doping and thickness. While surface charge from passivation can kill a MZ-JTE due to the discrete total charge in each zone, the bevel's continuum of charge makes it more tolerant of surface charge. However, from a fabrication standpoint there are significant challenges to overcome to produce such a shallow (10-15°) bevel angle. In contrast, a multi-zone JTE is relatively straightforward to process, although adding more zones comes at the cost of higher complexity.

The simulation results presented in this work demonstrate the capability of a negative bevel edge termination to achieve near 90% breakdown ideality for a 10-15° physical bevel angle. This is achieved by leveraging the effective bevel angle relationship. Increasing the depletion depth into the bevel compared to the drift depletion yields higher breakdown performance for the same given bevel angle. In this way, leveraging the effective bevel angle relationship can serve to increase the manufacturability of the bevel by relaxing the bevel angle requirement necessary for high breakdown performance. Not only does a 10° bevel angle take up less wafer real estate than a 1° bevel, but it is also much more feasible to fabricate.

Doping profiles for epitaxially-grown GaN p-n junctions are much more abrupt compared to implanted junctions characteristic of SiC power devices. As demonstrated by the analytical equations, the effective bevel angle relationship can be more easily leveraged with an abrupt junction (GaN) than with an implanted junction (SiC). This gives the bevel edge termination even more significance for GaN based power devices.

References

[1] M. J. Tadjer *et al.*, "Selective p-type Doping of GaN:Si by Mg Ion Implantation and Multicycle Rapid Thermal Annealing," *ECS J. Solid State Sci. Technol.*, vol. 5, no. 2, pp. P124–P127, Dec. 2016.

[2] W. Sung, A. Q. Huang, and B. J. Baliga, "Bevel junction termination extension - A new edge termination technique for 4H-SiC high-voltage devices," *IEEE Electron Device Lett.*, vol. 36, no. 6, pp. 594–596, 2015.

[3] H. K. Sung *et al.*, "Vertical and bevel-structured SiC etching techniques incorporating different gas mixture plasmas for various microelectronic applications," *Sci. Rep.*, vol. 7, no. 1, 2017.

[4] H. Ohta *et al.*, "Vertical GaN p-n Junction Diodes With High Breakdown Voltages Over 4 kV," *IEEE ELECTRON DEVICE Lett.*, vol. 36, no. 11, 2015.

[5] I. Stricklin *et al.*, "Investigation of interfacial impurities in m-plane GaN regrown p-n junctions for high-power vertical electronic devices," in *Wide Bandgap Power and Energy Devices and Applications III*, 2018, vol. 10754, p. 1.

[6] T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology*. Wiley, 2014.

[7] B. J. Baliga, *Fundamentals of power semiconductor devices*. Boston, MA: Springer US, 2008.

[8] X. Wang and J. A. Cooper, "Optimization of JTE Edge Terminations for 10 kV Power Devices in 4H-SiC," *Mater. Sci. Forum*, vol. 457–460, pp. 1257–1262, 2009.

[9] W. Tantraporn and V. A. K. Temple, "Multiple-Zone Single-Mask Junction Termination Extension-A High-Yield Near-Ideal Breakdown Voltage technology," 1987.

[10] H. Yilmaz, "Optimization and Surface Charge Sensitivity of High-Voltage Blocking Structures with Shallow Junctions," 1991.

[11] M. S. Adler and V. A. K. Temple, "A General Method for Predicting the Avalanche Breakdown Voltage of Negative Bevelled Devices," 1976.

[12] M. S. Adler and V. A. K. Temple, "Maximum surface and bulk electric fields at breakdown for planar and beveled devices," 1978.

[13] "Silvaco TCAD." [Online]. Available: https://www.silvaco.com/products/tcad.html. [Accessed: 21-Aug-2019].

[14] A. Armstrong *et al.*, "High voltage and high current density vertical GaN power diodes," 2016.

[15] J. R. Dickerson *et al.*, "Vertical GaN Power Diodes With a Bilayer Edge Termination," *IEEE Trans. Electron Devices*, vol. 63, no. 1, p. 419, 2016.

[16] J. J. Wierer, J. R. Dickerson, A. A. Allerman, A. M. Armstrong, M. H. Crawford, and R. J. Kaplar, "Simulations of Junction Termination Extensions in Vertical GaN Power Diodes," *IEEE Trans. Electron Devices*, vol. 64, no. 5, pp. 2291–2297, 2017.