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Limitations in Impact Ionization Modeling for Predicting Breakdown in Wide Bandgap Power Semiconductors

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The prediction of breakdown voltage is a critical aspect of modeling for power semiconductor devices. High power devices employ a vertical device architecture to maximize the current carrying capability and breakdown voltage for a given die area. To predict breakdown voltage, impact ionization models such as the one developed by Selberherr can be used to calculate avalanche multiplication given an applied electric field. When the avalanche multiplication factor reaches one, the device is considered to be in breakdown. The inputs to the Selberherr impact ionization model are two coefficients α_0 and $\mathcal{E}_0$. From this model the critical electric field can be calculated as a function of doping: this critical electric field is then used to calculate the breakdown voltage.

Impact ionization models, such as Selberherr's model, were created to model ionization in a one-dimensional structure. For this one-dimensional scenario, there are an infinite set of solutions to the ionization model that will yield a specific critical electric field at a given doping level. The ionization coefficients α_0 and $\mathcal{E}_0$ are exponentially dependent and for any given α_0 there are an infinite number of solutions for $\mathcal{E}_0$ that will produce an identical solution to the ionization model. As these coefficients increase, critical electric field becomes a stronger function of doping, and as the coefficients decrease the dependency becomes weaker. In a one-dimensional ideal diode, each of these solutions will yield the same breakdown voltage prediction for a given critical electric field at a specified doping level. In addition, the ionization equation will yield the same critical electric field for a range of input coefficients (α_0 and $\mathcal{E}_0$) and these coefficients will trend up together (high ionization coefficients) and trend down together (low ionization coefficients) while still producing the same solution for critical electric field at a given doping. In this way, the solutions are nonunique and the choice of impact ionization coefficients are inconsequential when solving for a critical electric field.

When considering a two- or three-dimensional model, the selection of impact ionization coefficients becomes critically important as the infinite set of solutions to the impact ionization model no longer produces a unique breakdown voltage prediction. With a multi-dimensional model, the predicted breakdown voltage can become higher than the ideal breakdown voltage when the ionization coefficients are too low, and the breakdown voltage will drop as the ionization coefficients are increased. In addition, it is noted in simulations that the impact ionization becomes very localized around the point of highest electric field when considering high ionization coefficients, and conversely the ionization becomes very delocalized for low ionization coefficients.

A literature review of reported impact ionization coefficients in GaN (α_0 and $\mathcal{E}_0$) yields a vast range of values for critical electric field and a varying dependence on doping. This work demonstrates the impact of ionization coefficients on breakdown and the discrepancy between one-dimensional and two-dimensional models in predicting breakdown voltage. A comparison of impact ionization and breakdown voltage is shown in modeling for an ideal one-dimensional diode and a two-dimensional diode with a step-etched junction termination extension (JTE).

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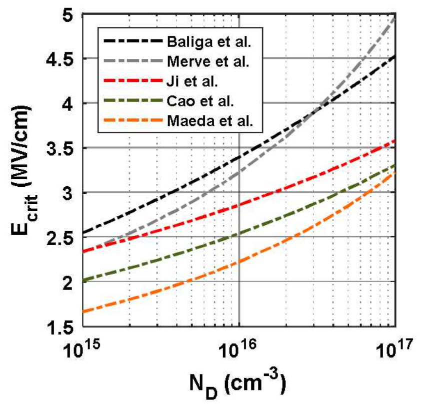


Fig. 1: Dependency of critical electric field on drift doping for GaN given impact ionization coefficients reported in literature. Notice that the slopes of these curves can vary considerably.

TABLE I. IMPACT IONIZATION PARAMETERS FOR GAN

Reference	Electrons		Holes	
	α_0 (cm^{-1})	$\mathcal{E}_0$ (V/cm)	α_0 (cm^{-1})	$\mathcal{E}_0$ (V/cm)
Cao et al.	4.48×10^8	3.39×10^7	7.13×10^6	1.46×10^7
Ji et al.	2.11×10^9	3.69×10^7	4.39×10^6	1.80×10^7
Maeda et al.[a]	1.30×10^6	1.18×10^7	1.30×10^6	1.18×10^7
Merve et al.	1.50×10^5	1.41×10^7	6.40×10^5	1.45×10^7

[a] Evaluated at room temperature

Impact Ionization Model: $$\alpha = \alpha_0 \cdot e^{-\left(\frac{\mathcal{E}_0}{\mathcal{E}}\right)}$$

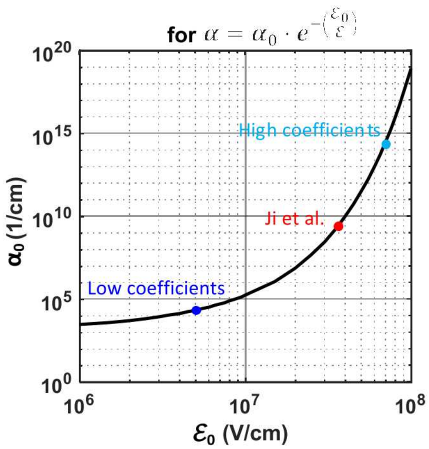
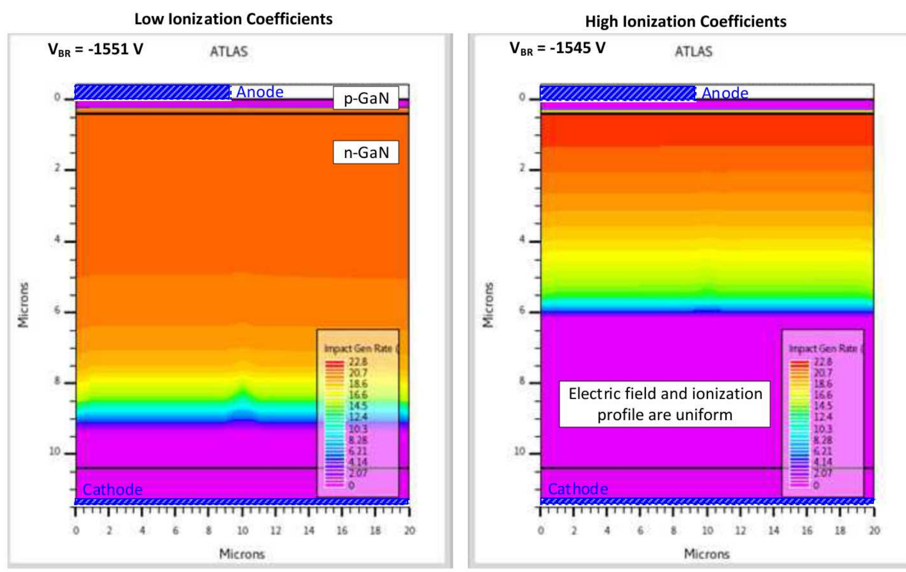


Fig. 2: This curve represents the non-unique solutions to the impact ionization equation that will yield a critical electric field of 3.0 MV/cm at a doping of 2×10^{16} cm^{-3} for an ideal one-dimensional diode.



One-Dimensional Ideal Model

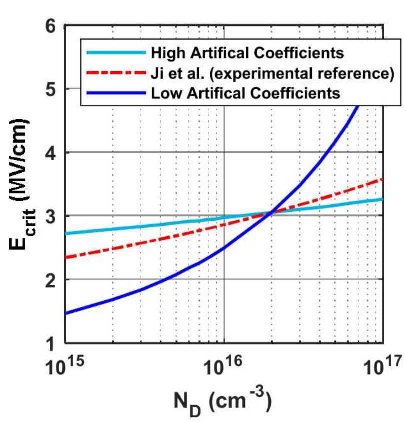
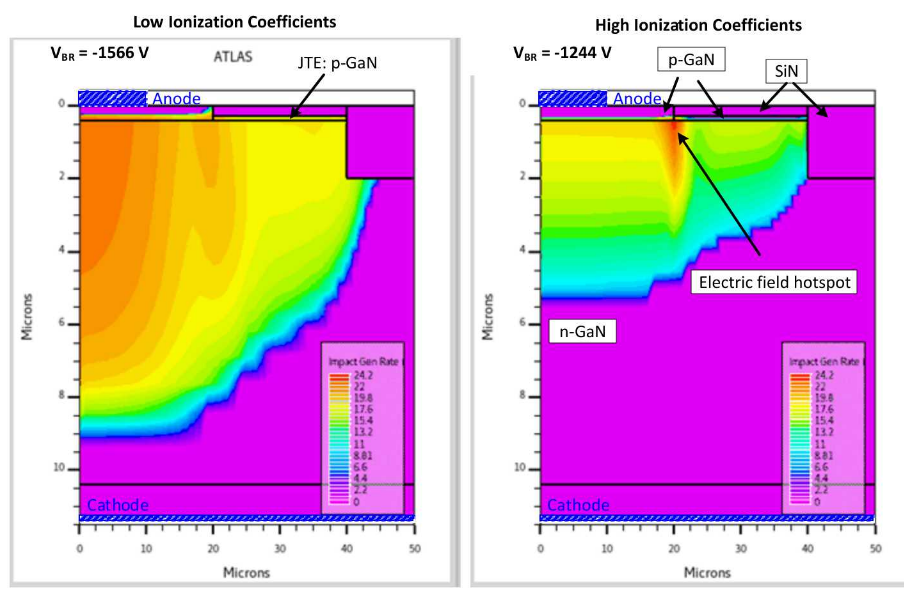


Fig. 3: Example of critical electric field versus drift doping curves given arbitrarily selected high and low impact ionization coefficients. Notice that the critical electric field is a weak function of doping with high ionization coefficients, but a strong function of doping with low coefficients.



Two-Dimensional Model with Step-Etched JTE