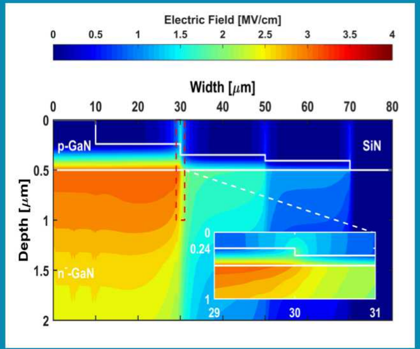
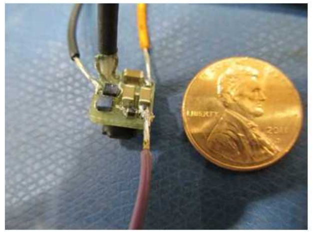
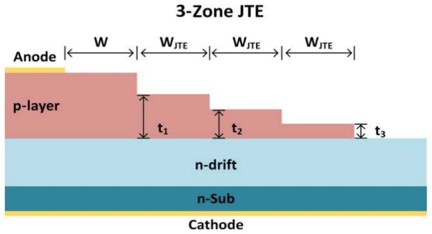
edtm 2020
Electron Devices Technology and Manufacturing Conference

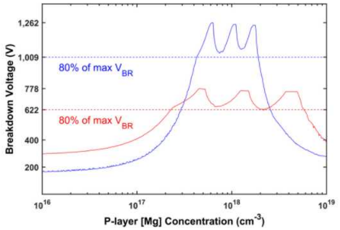
SAND2020-3659C

Simulation and Design of Step-Etched Junction Termination Extensions for GaN Power Diodes









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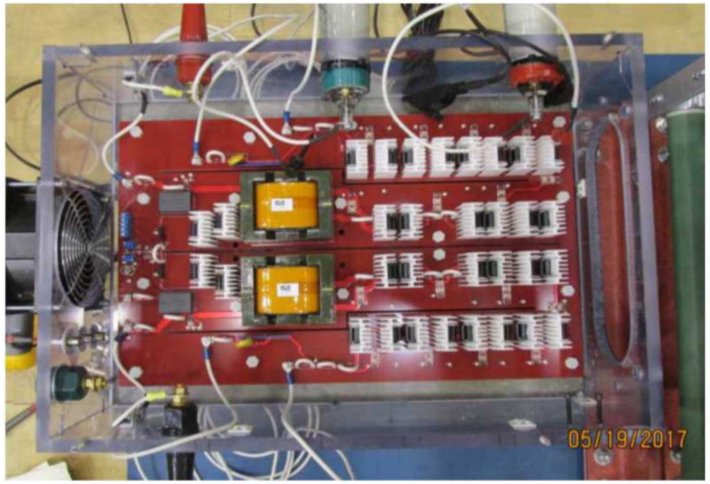
Outline

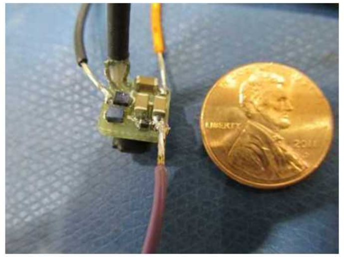
- Motivation for GaN
- Impact Ionization
- Edge Termination
- Single Zone JTE
- Three Zone JTE

Wide-Bandgap Materials Enable Compact Power Converters

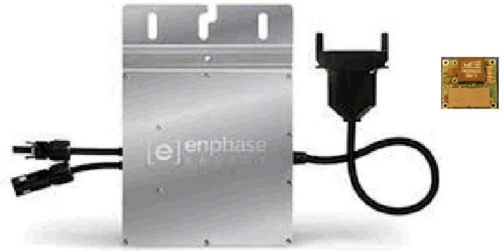


SNL SiC hybrid switched-capacitor boost converter (ARPA-E)

- **First prototype: 0.5 kV → 10.1 kV (gain = 16.8) at 2.6 kW, 95.3% efficient, 410 in^3**
- **Second prototype: +2% efficiency, 55% volume**



SNL GaN HEMT "Coin Converter"
90 V, 90 mA → 215 W/in^3

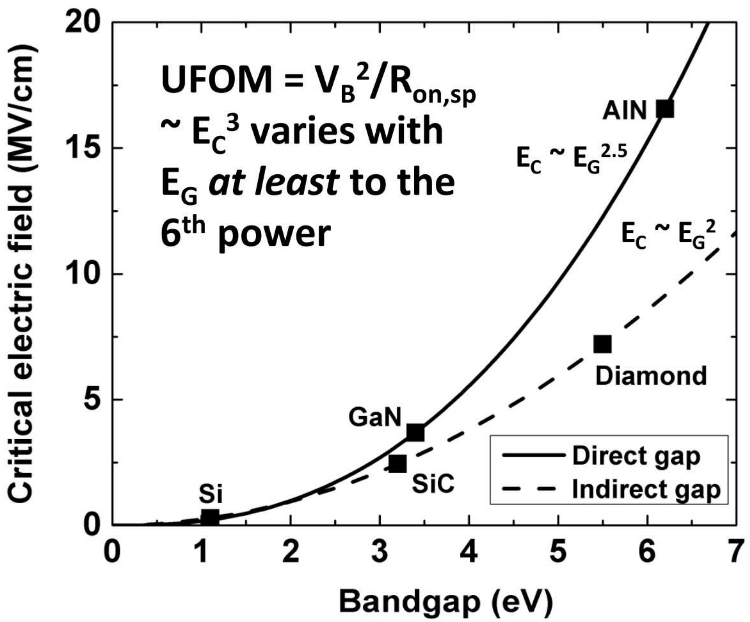


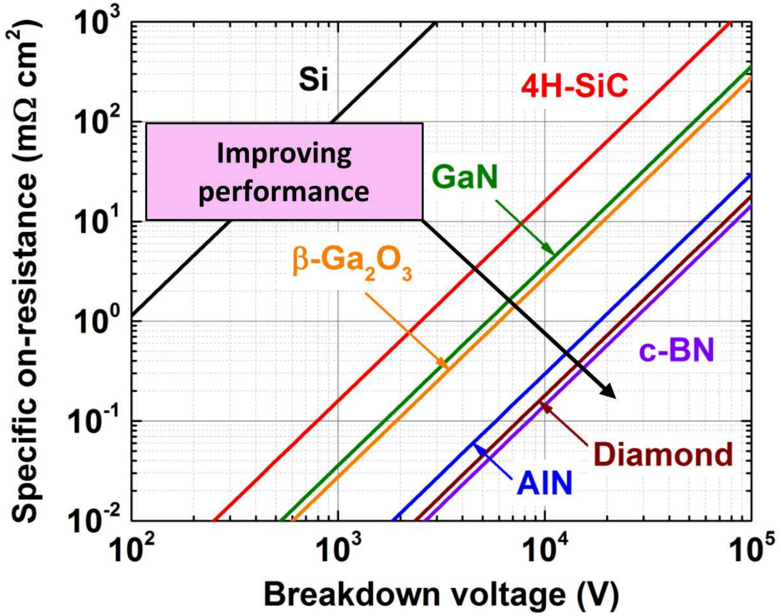
SOA commercial microinverter
250 W in 59 in^3 → 4.2 W/in^3

Over an Order of Magnitude Improvement in Power Density is Enabled by WBG and UWBG Semiconductors Compared to Si

Benefits of Wide-Bandgap Semiconductors

Fundamental Materials Capabilities	Conventional		WBG		UWBG
Property	**Si**	**GaAs**	**4H-SiC**	**GaN**	**AlN**
Bandgap (eV)	1.1	1.4	3.3	3.4	6.0
Critical Electric Field (MV/cm)	0.3	0.4	2.0	4.9	13.0

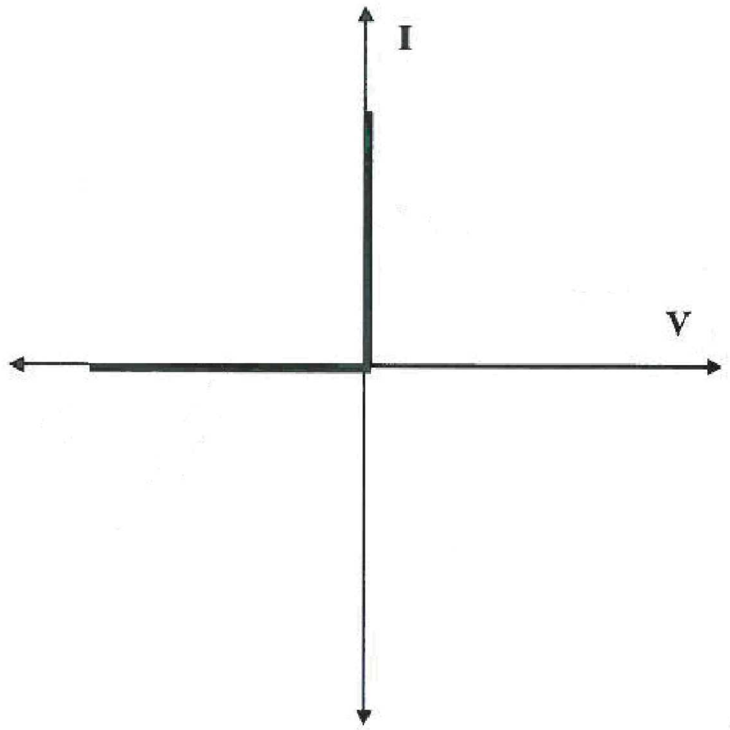




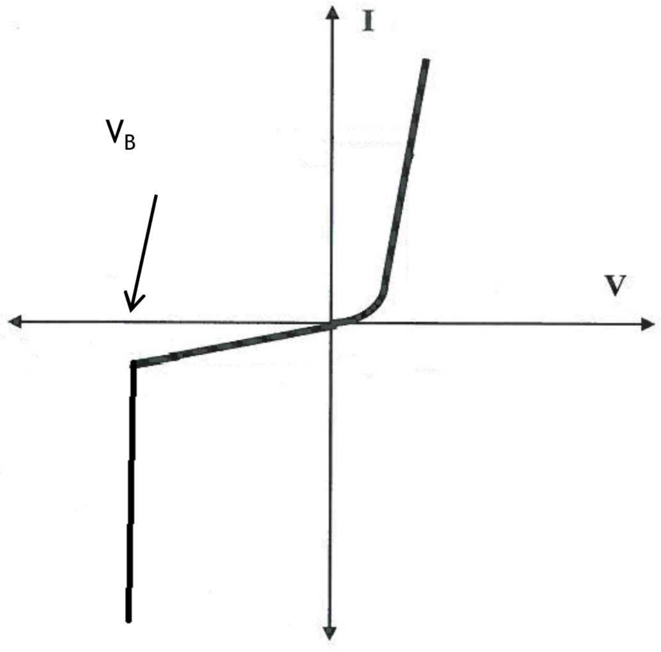
Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$

Hudgins et al., *IEEE Trans. Pwr. Elec.* 18, 907 (2003); J. Y. Tsao et al., *Adv. Elec. Mat.* 4 1600501 2017

Power Diodes

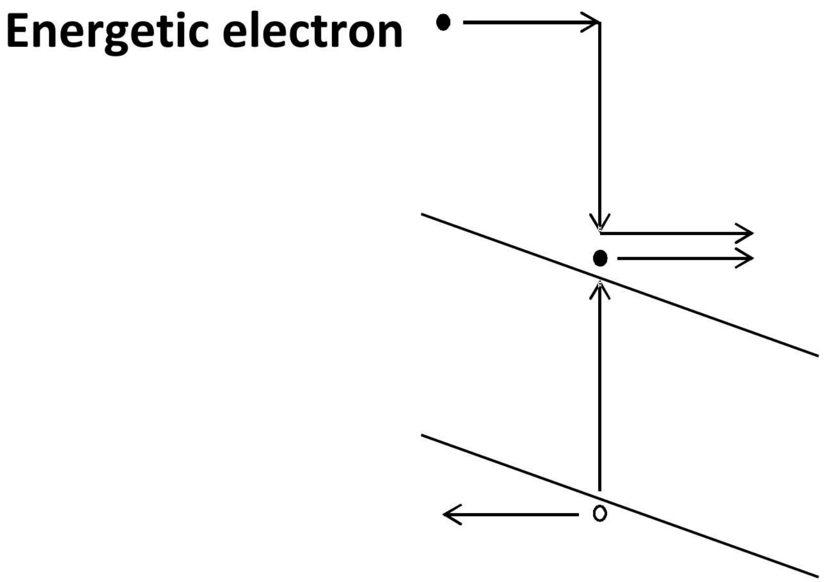


An ideal diode is the perfect switch.



Normal device I-V curve. Reverse blocking limited by the breakdown voltage V_B.

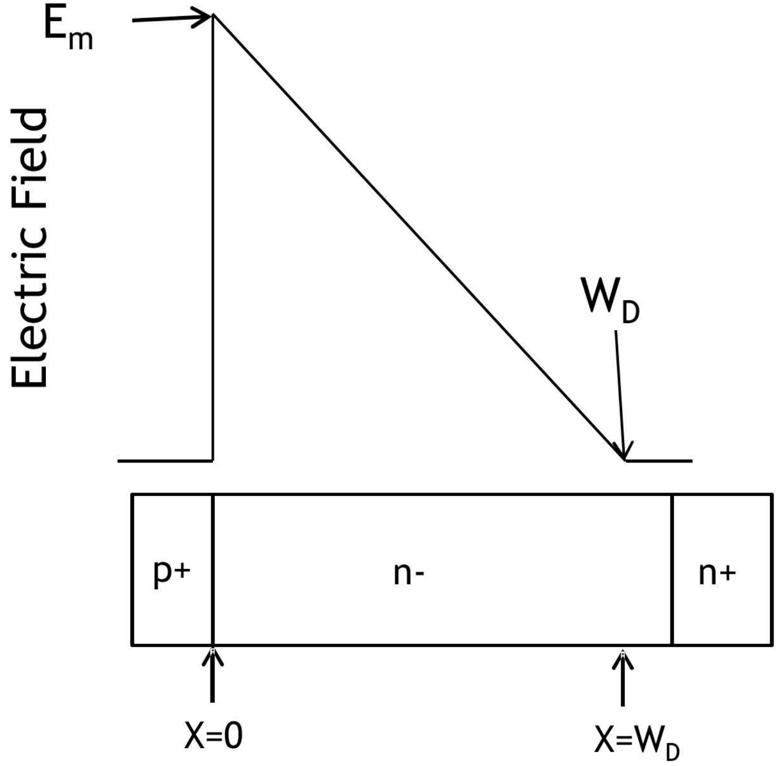
Impact Ionization



Impact ionization:

1. **An energetic carrier collides with an atom.**
2. **Energy is transferred to the atom and creates an electron-hole pair.**

The 'Critical' Electric Field



$$W_\mathrm{D} = \sqrt{\frac{2\varepsilon V_a}{q N_D}} \qquad E_\mathrm{m} = \sqrt{\frac{2 q N_D V_a}{\varepsilon}} = \frac{W_\mathrm{D} q N_D}{\varepsilon}$$

$$M_n(x) = \frac{\exp\left[\int_0^{W_D} (\alpha_\mathrm{n} - \alpha_\mathrm{p})\mathrm{d}x\right]}{1 - \int_0^{W_\mathrm{D}} \alpha_\mathrm{p} \exp\left[\int_x^{W_D} (\alpha_\mathrm{n} - \alpha_\mathrm{p})\mathrm{d}x'\right]\mathrm{d}x}$$

$$M_p(x) = \frac{\exp\left[-\int_0^{W_D} (\alpha_\mathrm{p} - \alpha_\mathrm{n})\mathrm{d}x\right]}{1 - \int_0^{W_\mathrm{D}} \alpha_\mathrm{n} \exp\left[-\int_x^{W_D} (\alpha_\mathrm{p} - \alpha_\mathrm{n})\mathrm{d}x'\right]\mathrm{d}x}$$

$$\int_0^{W_\mathrm{D}} \alpha_\mathrm{p} \exp\left[\int_x^{W_D} (\alpha_\mathrm{n} - \alpha_\mathrm{p})\mathrm{d}x'\right]\mathrm{d}x = \int_0^{W_\mathrm{D}} \alpha_\mathrm{n} \exp\left[-\int_x^{W_D} (\alpha_\mathrm{p} - \alpha_\mathrm{n})\mathrm{d}x'\right]\mathrm{d}x = 1$$

The critical field is defined as the maximum electric field that leads to avalanche breakdown in a 1D analytical model.

Selberherr's Impact Ionization Model

Selberherr's Impact Ionization model relates the impact ionization coefficients, α_n and α_p, to the local electric field using three fitting parameters.

$$\alpha_n = A_N \exp\left[-\left(\frac{B_N}{E}\right)^{l_N}\right] \qquad \alpha_p = A_P \exp\left[-\left(\frac{B_P}{E}\right)^{l_P}\right]$$

IMPACT IONIZATION PARAMETERS FOR GAN

Reference	Electrons		Holes	
	A_N (cm^{-1})	B_N (V/cm)	A_P (cm^{-1})	B_P (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

[a] Evaluated at room temperature

These three reports assume $l_N = 1$ and $l_P = 1$

Selberherr, S. *Analysis and Simulation of Semiconductor Devices*. Wien, New York: Springer-Verlag, 1984.

Edge Terminations

Edge terminations are required to control the electric fields near the pn junction and to prevent premature breakdown of devices.

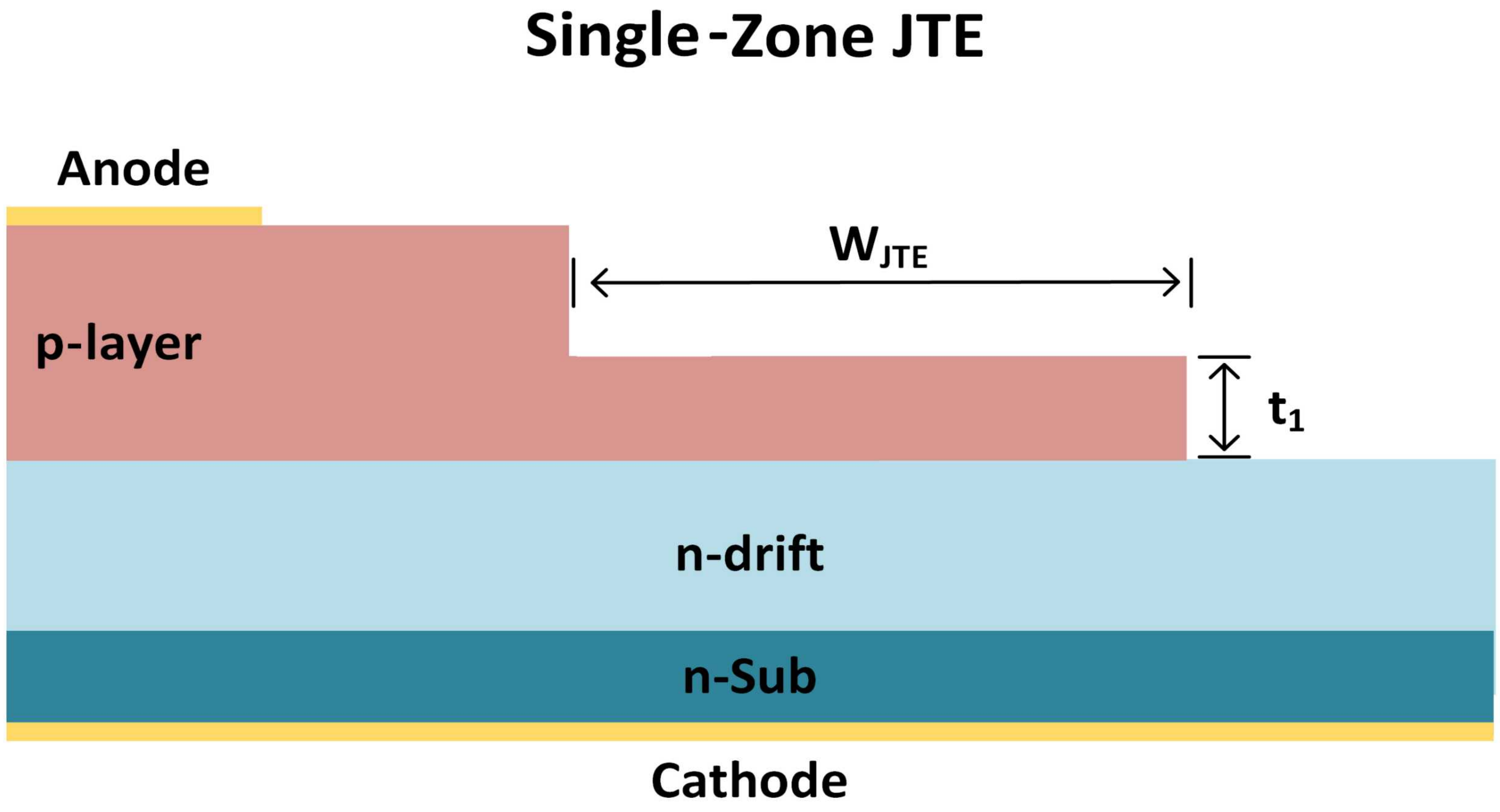
Several methods exist, such as guard rings, junction-termination extensions (JTE), and beveled terminations.

The focus of this work is on the use of JTEs. Typically, JTE structures are fabricated by dopant implantation at the surface of the device.

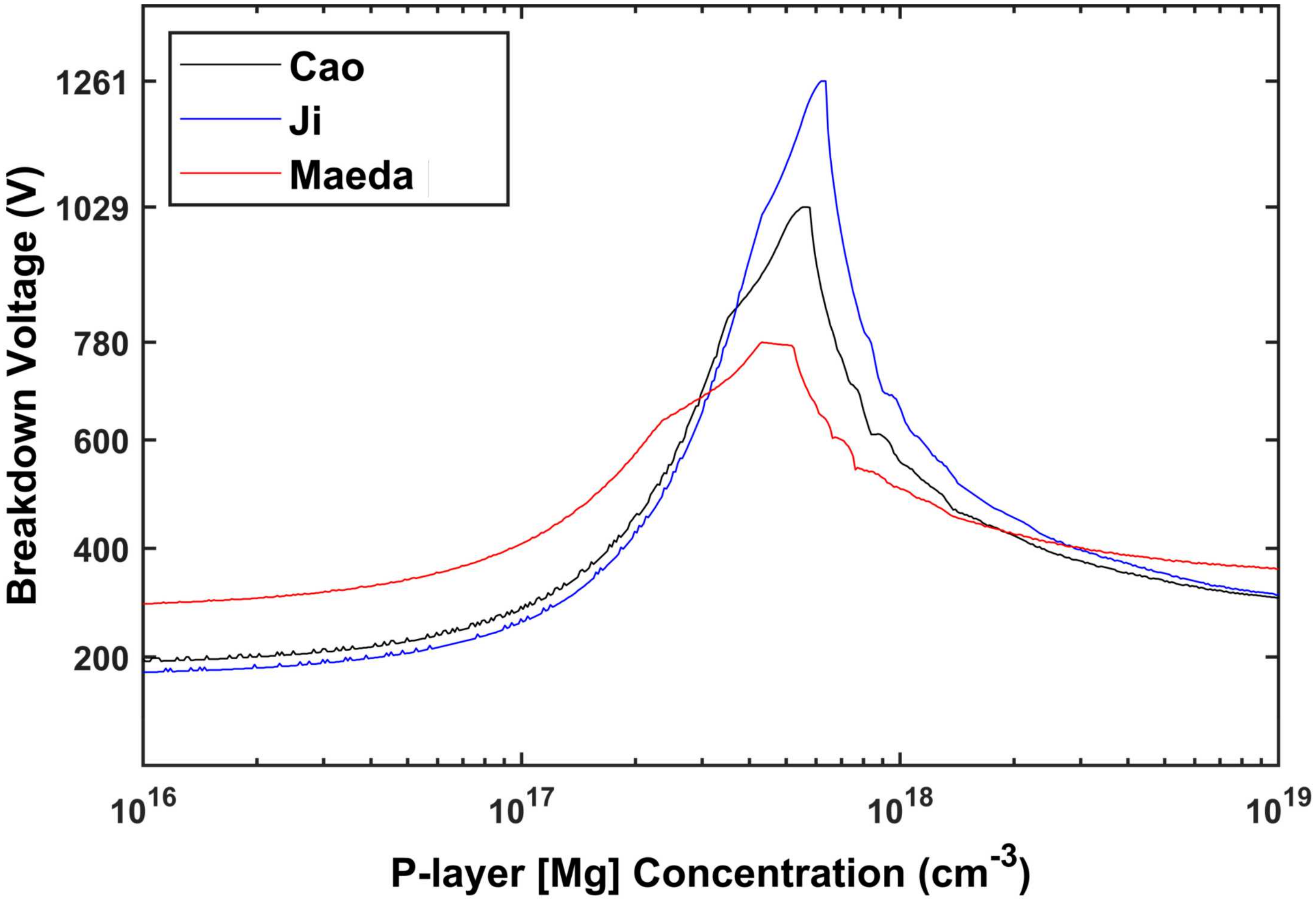
However, due to the present difficulty of implanting Mg in GaN, an alternative method would be to selectively etch back the p-GaN region to a target thickness.

The JTE total dose is then the doping concentration and thickness product of the remaining p-type material.

A Single Zone Etched JTE



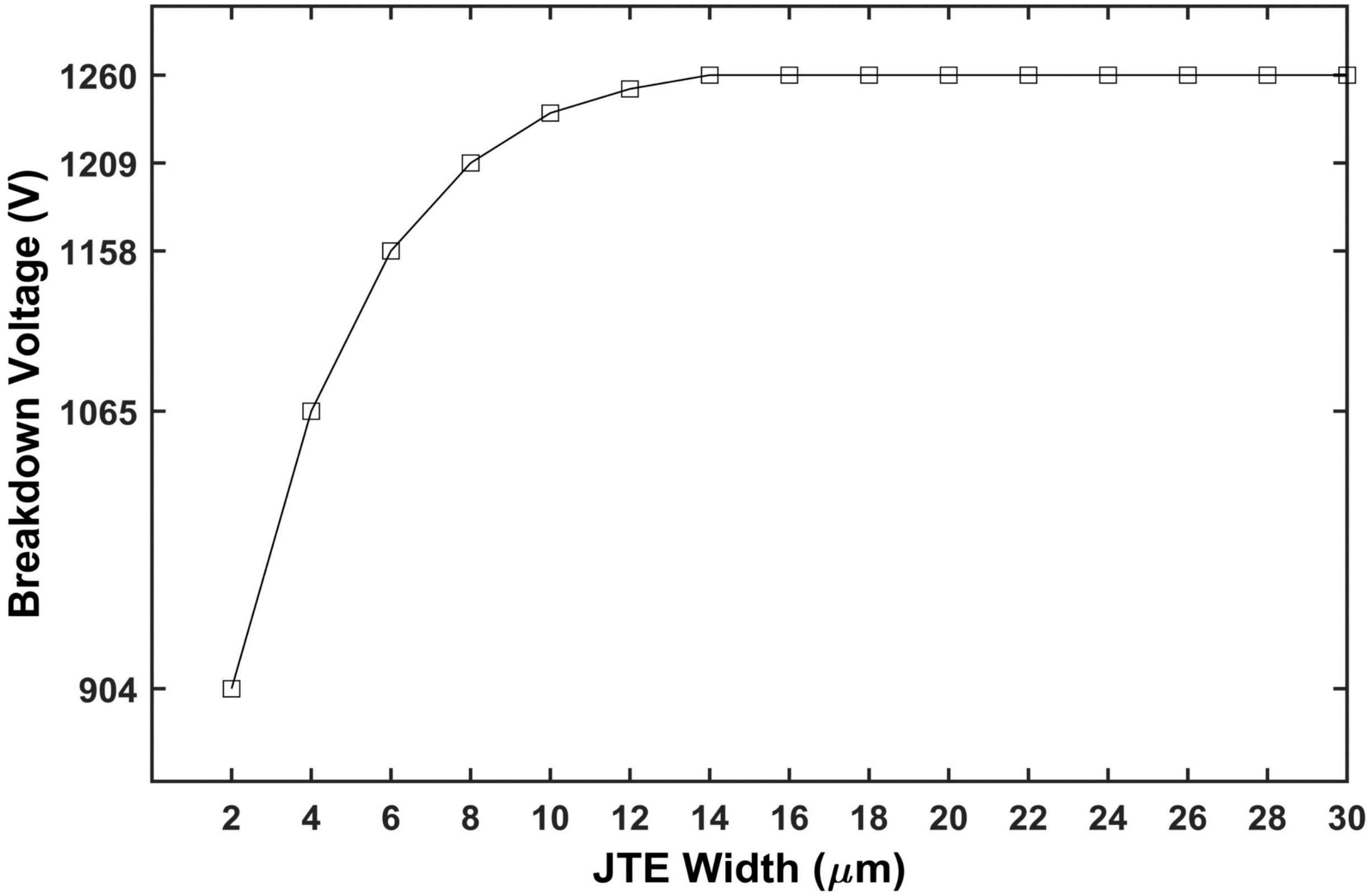
Breakdown of a Single-Zone JTE



- The doping of the p-region along with the thickness, t_1, of the JTE region is critical for determining the dose of the JTE.
- In this example, the thickness of t_1 is set to 260 nm and the value of WJTE is set to 20 μm, then as a function of p-region doping, a single JTE is expected to produce a peak breakdown at the optimal JTE dose as shown here.
- The peak profile depends entirely on the impact ionization parameters used.

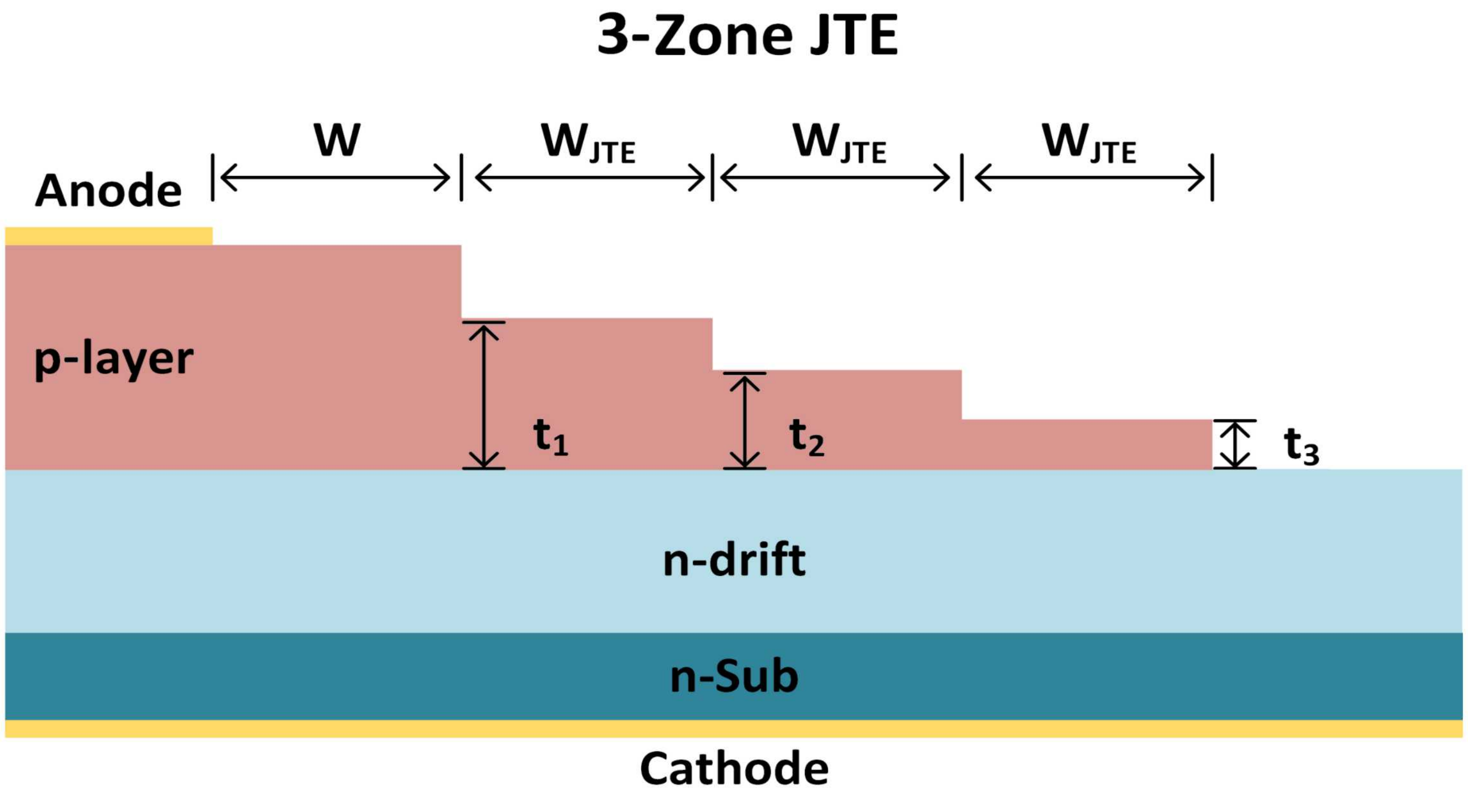
All simulations use Silvaco ATLAS TCAD software
www.Silvaco.com

W_{JTE}, the Width of the JTE Region

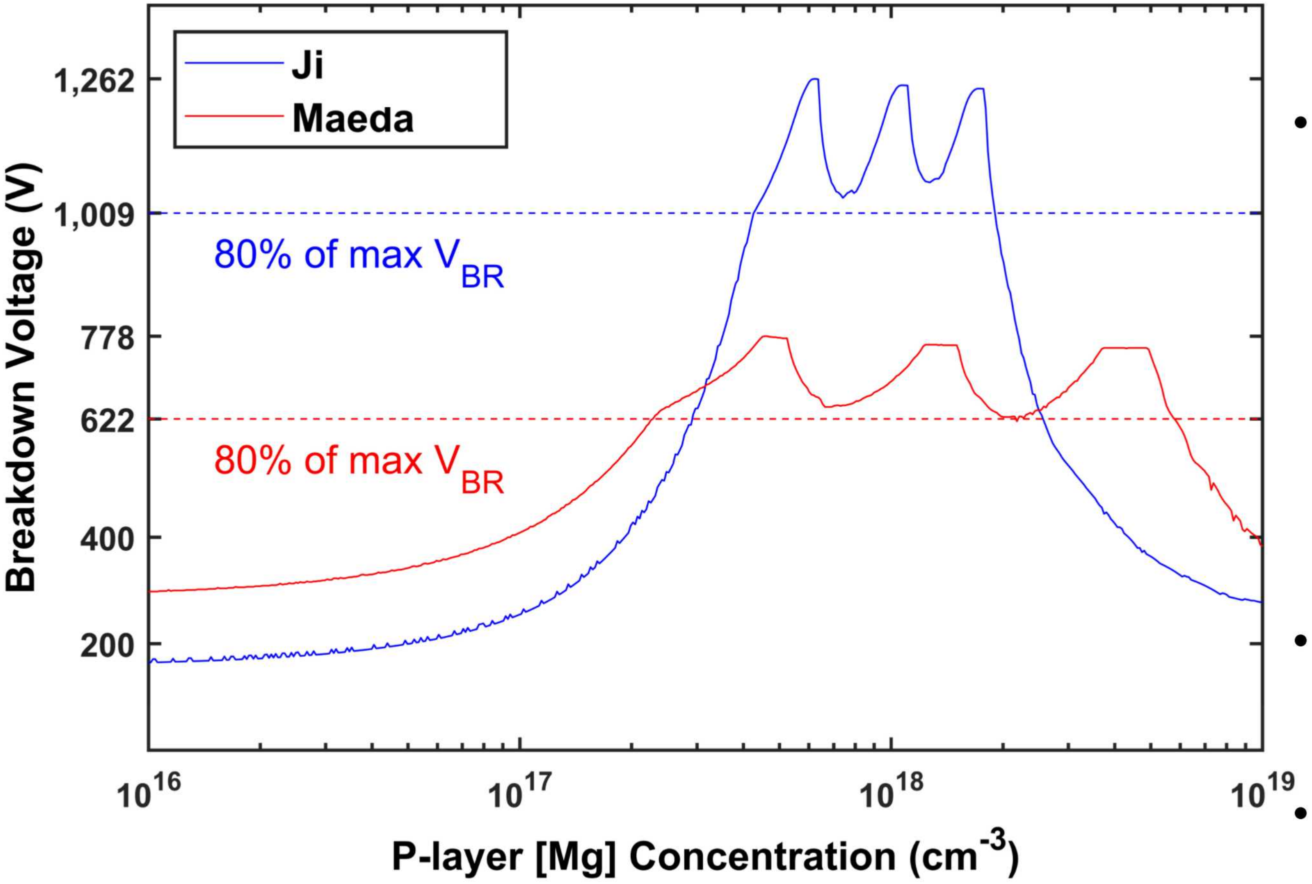


- The value of W_{JTE} can decrease the breakdown field if it is too small.
- In this sweep of W_{JTE}, the value of t_1 and the doping resulting in the peak breakdown in the previous slide are utilized. Additionally we use the impact ionization values of Ji et al.

A Three Zone Etched JTE

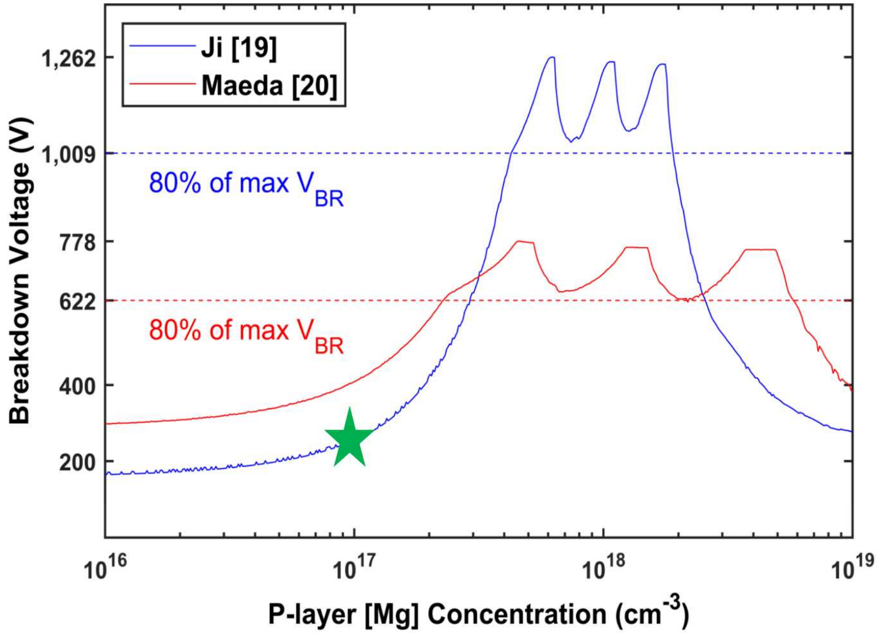


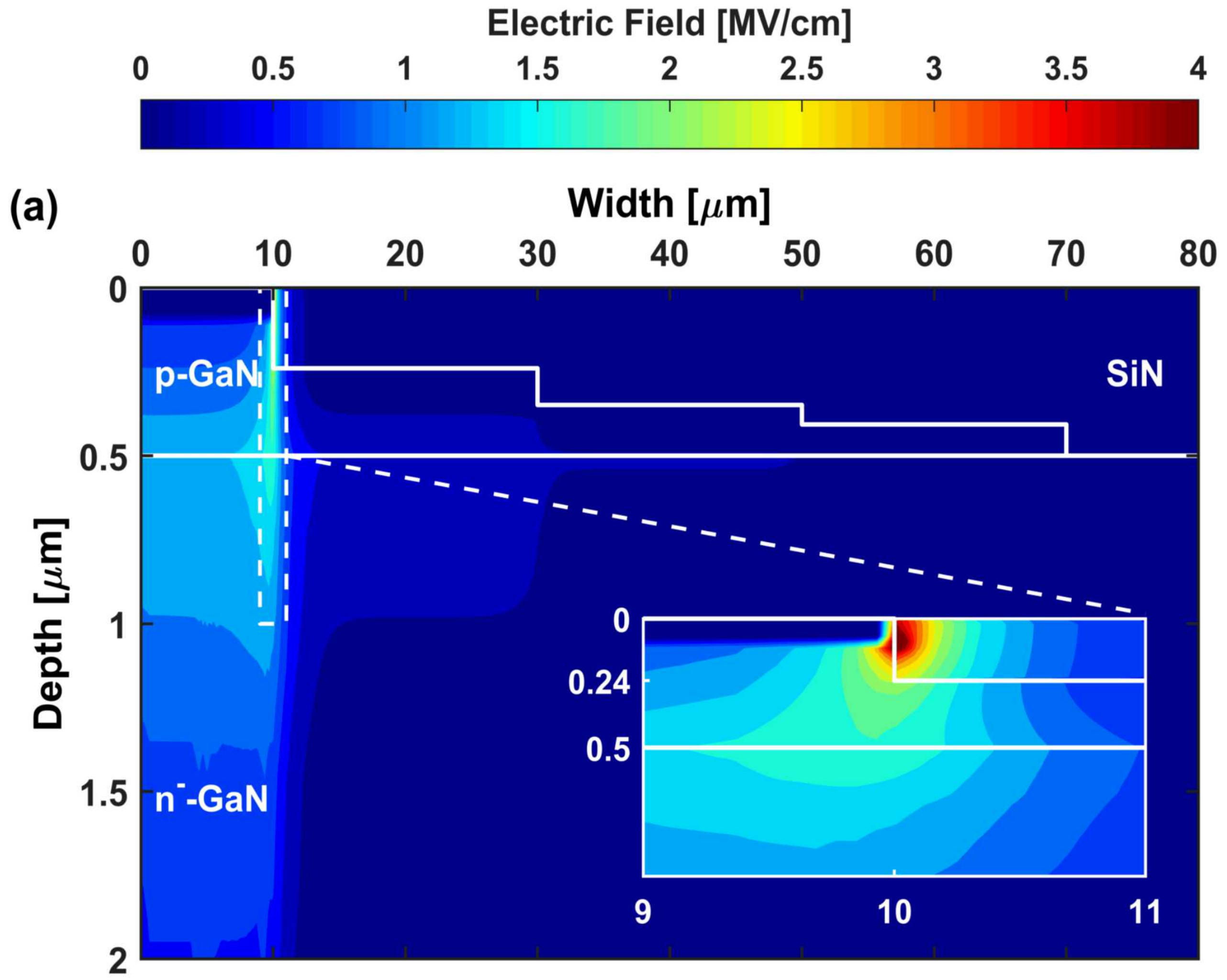
Breakdown of a Three-Zone JTE



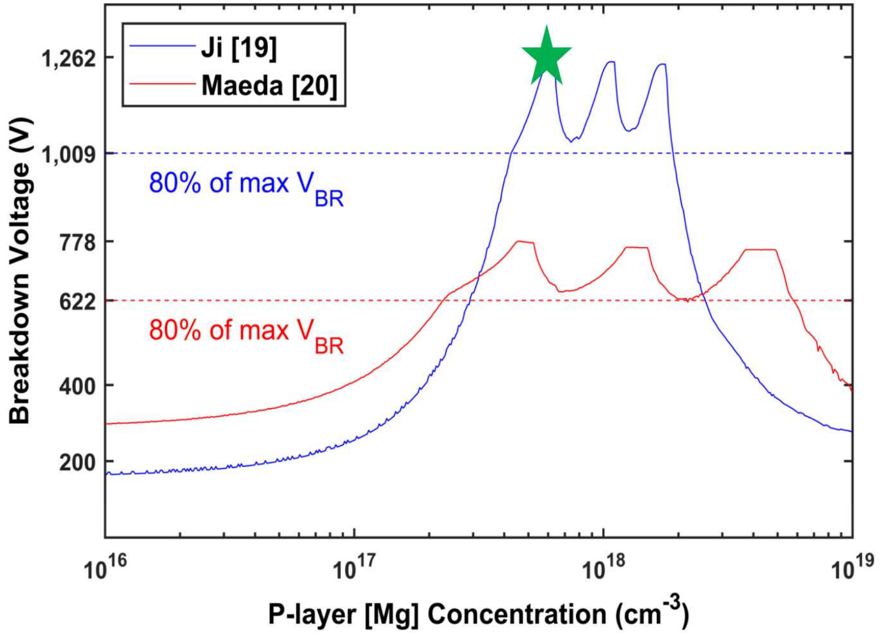
- The range of p-region [Mg] concentrations that produce optimal breakdown values increases by adding additional JTE zones.
- In this figure, the design constraint was arbitrarily selected to require the breakdown to achieve 80% of the theoretical max. This resulted in t1, t2, and t3 being set to 260, 151, and 93 nm respectively for the impact ionization coefficients for Ji. For Maeda, t1, t2, and t3 were set to 260, 91, and 32 respectively.
- Each JTE region used the same value of WJTE = 20 μm.
- The impact of the different impact ionization terms is more apparent here.

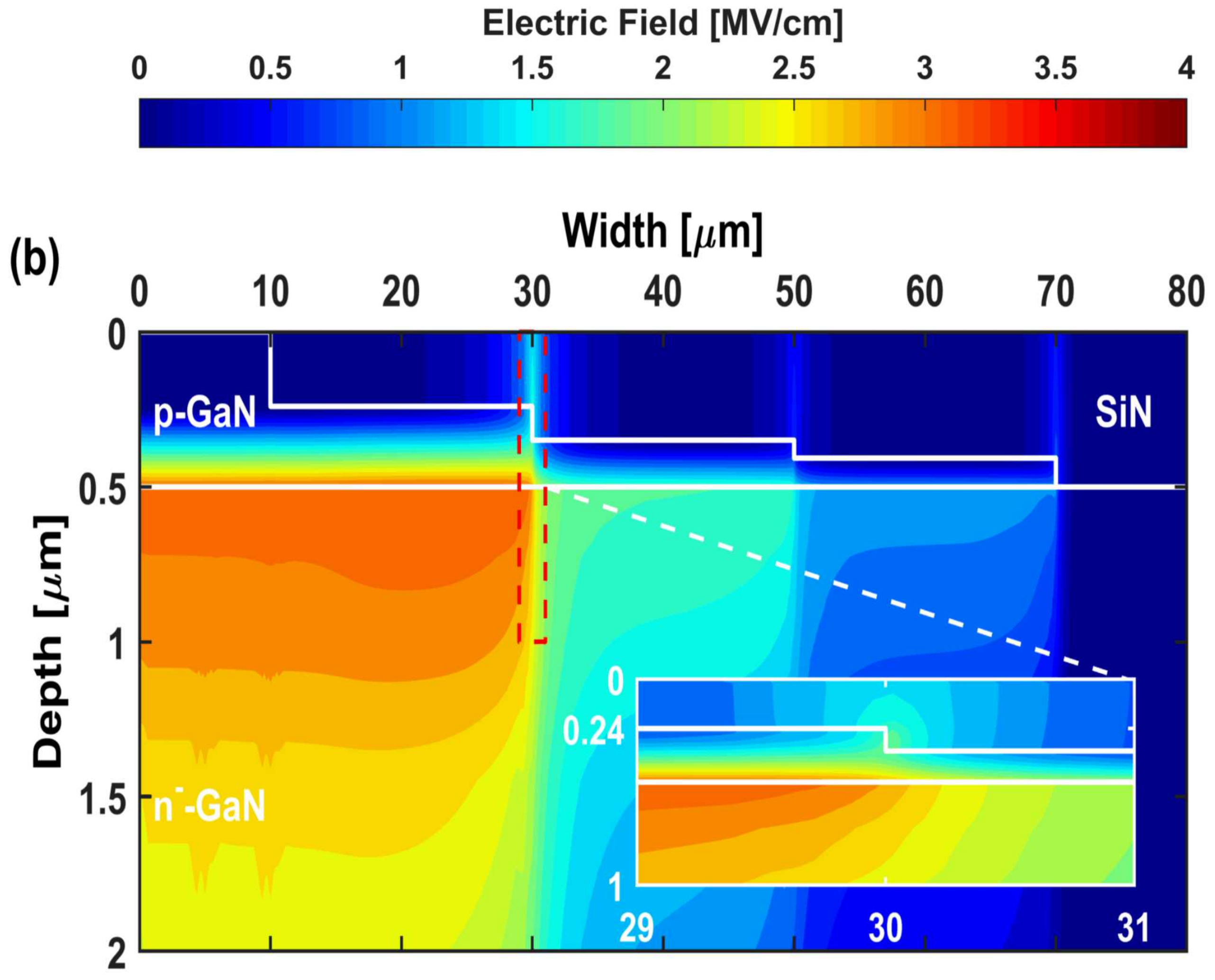
Field Profile at 10^{17} cm^{-3} [Mg]



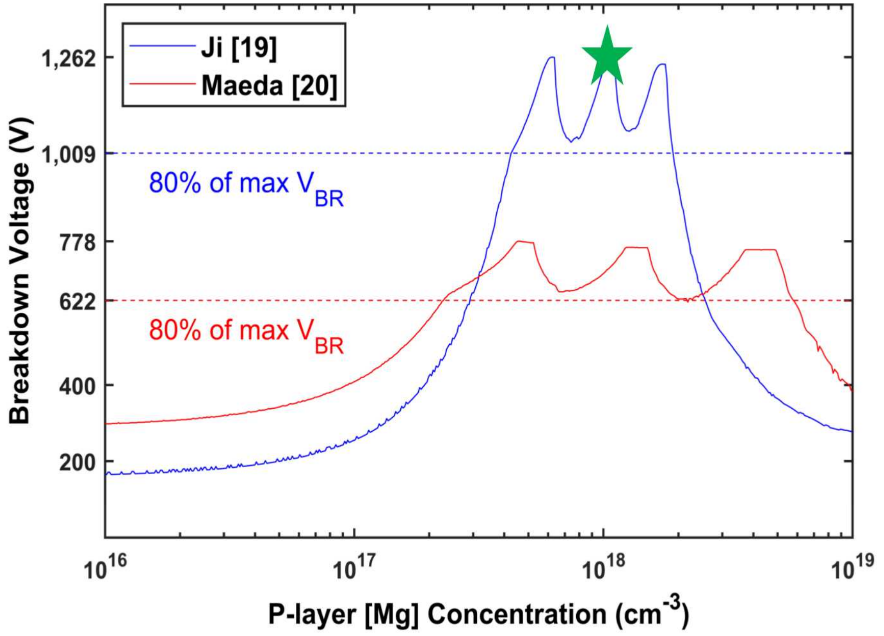


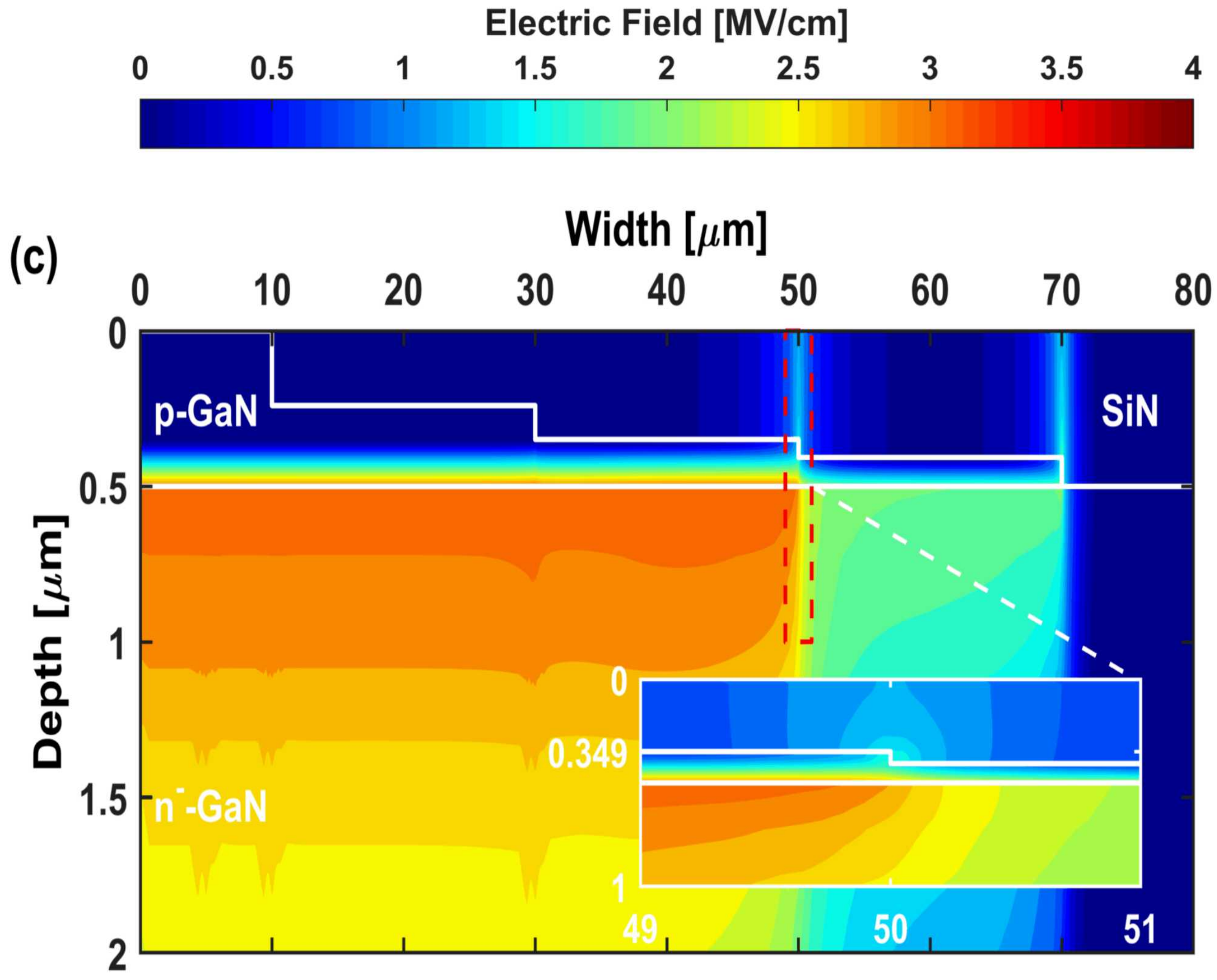
Field Profile at 6.3×10^{17} cm^{-3} [Mg]



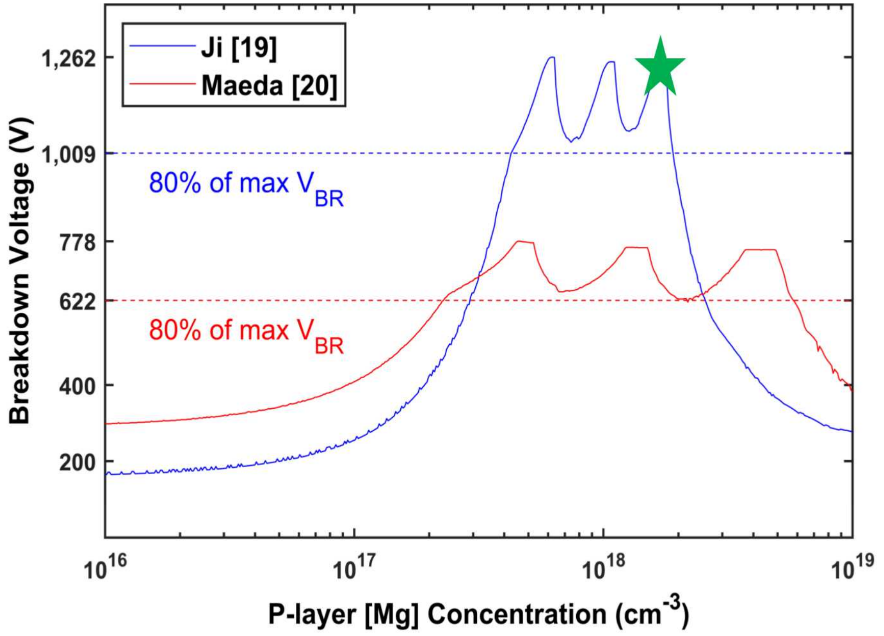


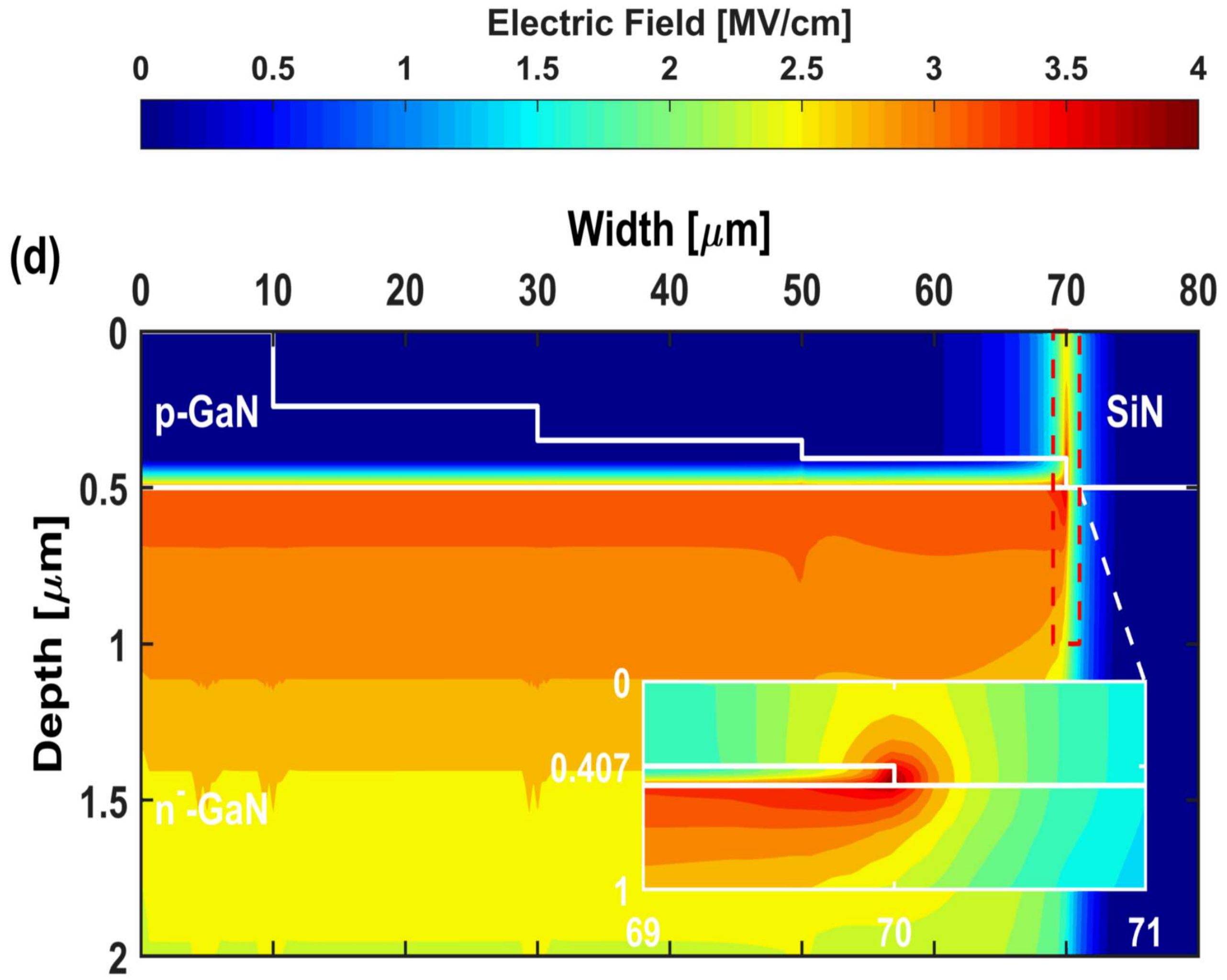
Field Profile at 1.1×10^{18} cm^{-3} [Mg]



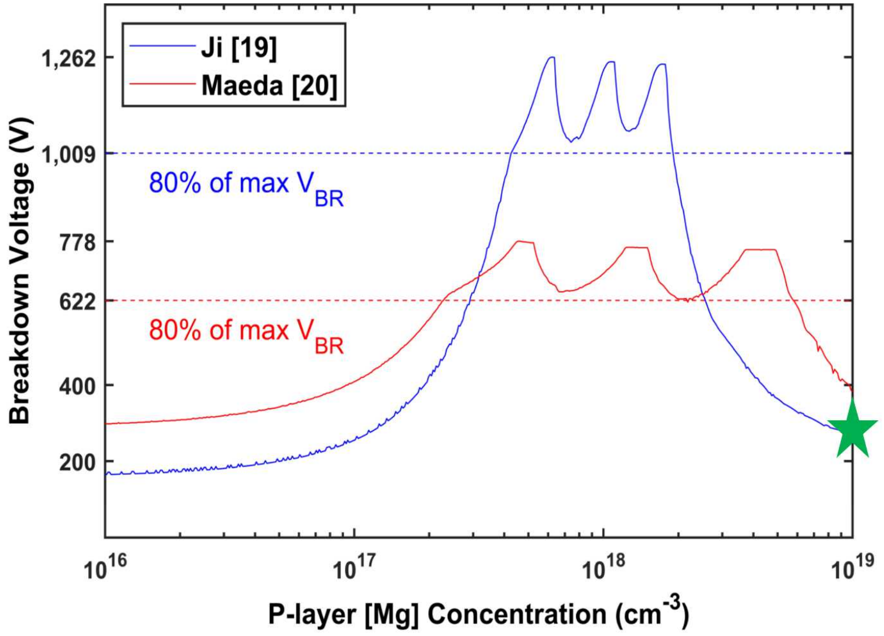


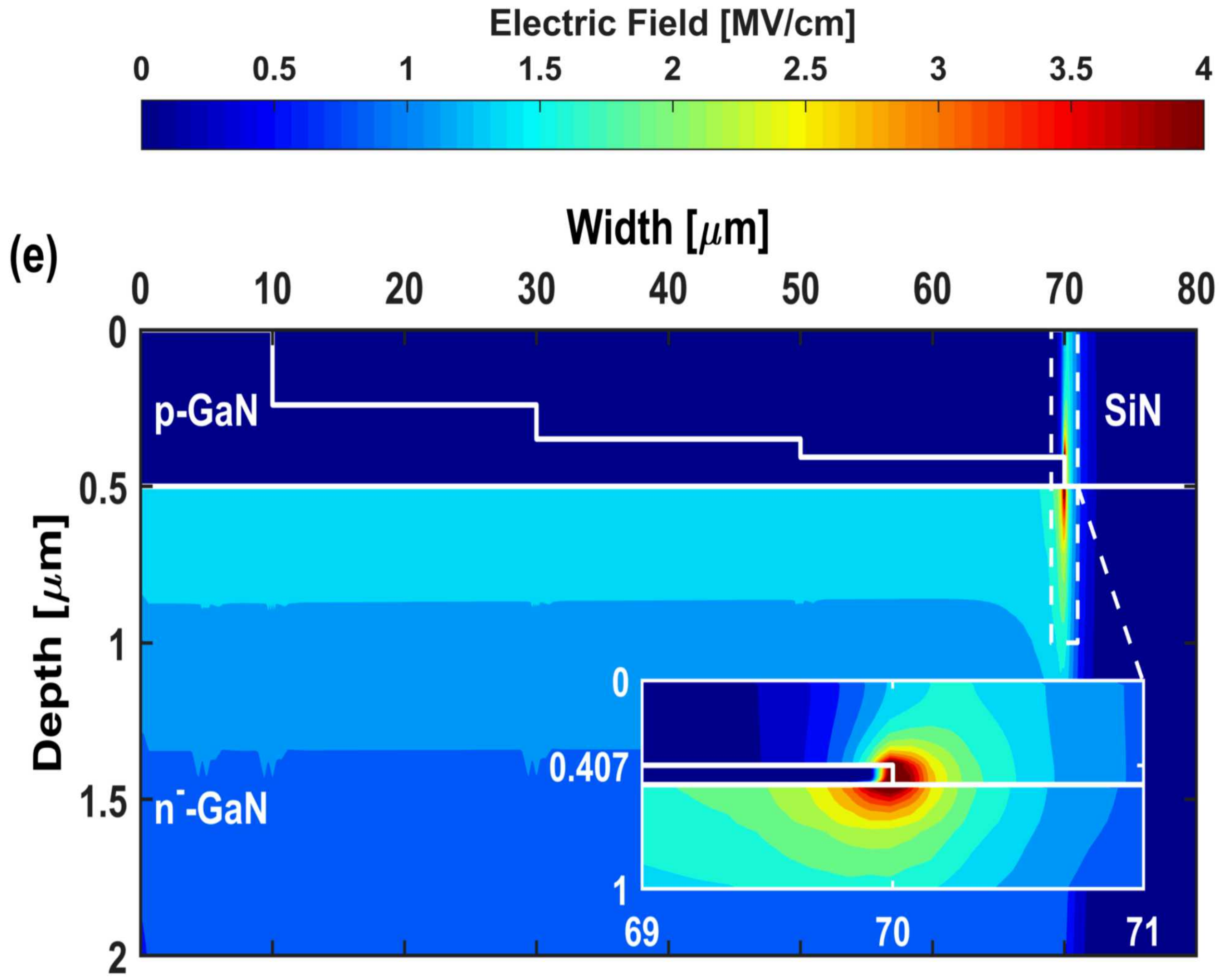
Field Profile at 1.7×10^{18} cm^{-3} [Mg]





Field Profile at 10^{19} cm^{-3} [Mg]





Conclusion

- The Etched Multi-Zone JTE has the potential to increase the effectiveness of the edge termination by allowing more precise control of the JTE dose.
- The impact ionization coefficients used can alter the fabrication tolerance of a given multi-zone JTE design.
- Future work will investigate the impact of surface charges from oxide traps and etch damage.
- Sandia National Laboratories is currently investigating the effectiveness of the multi-zone JTE design and results will be presented at a future time.