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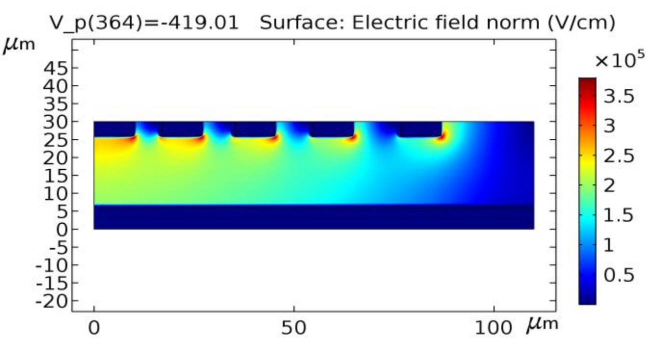
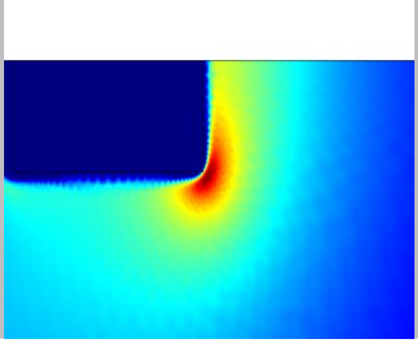
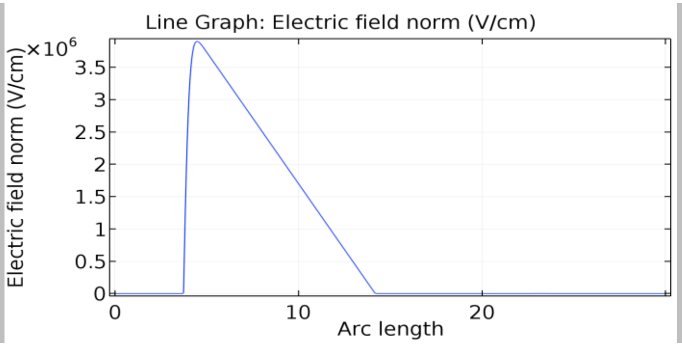




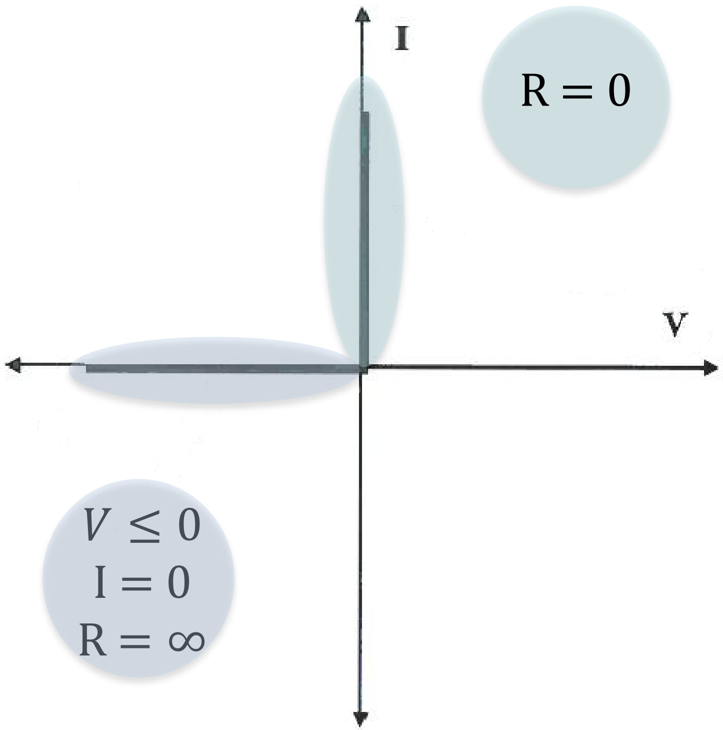


Modeling of Avalanche Breakdown in Silicon and Gallium Nitride High-Voltage Diodes using COMSOL®

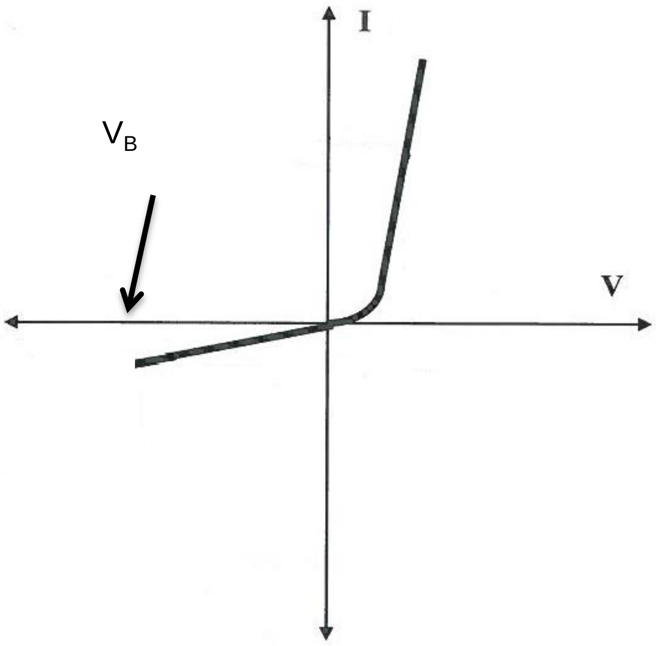
J. Dickerson, R. J. Kaplar, and G. Pickrell

This presentation describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Sandia National Laboratories is a multimission 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

Power Diodes



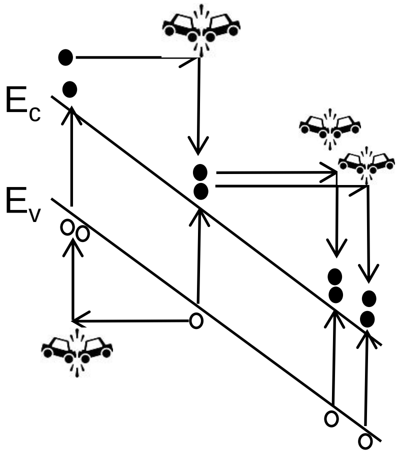
An ideal diode is the perfect switch.



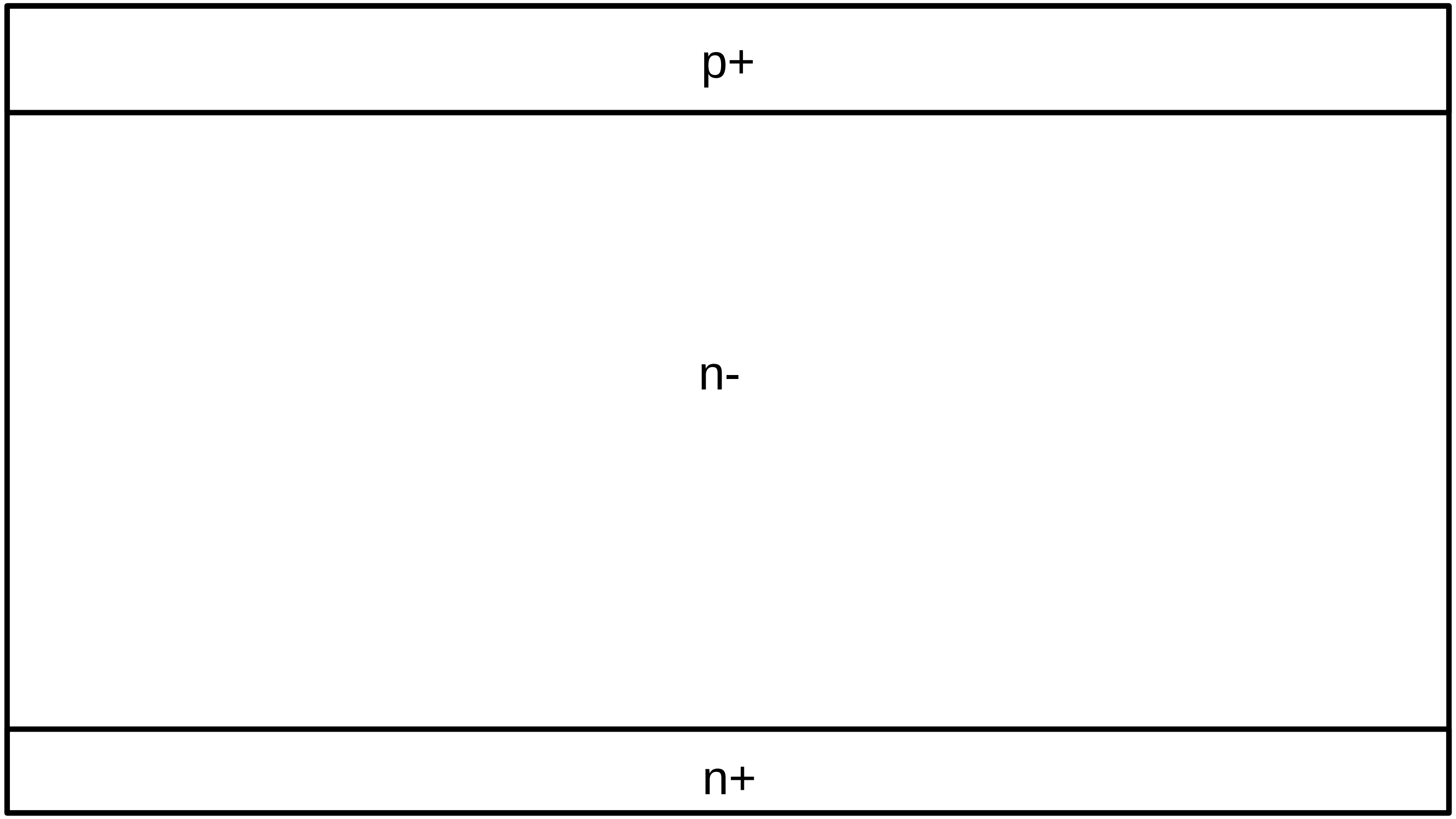
Normal device I-V curve.

Reverse blocking limited by the breakdown voltage V_B.

Impact Ionization and Avalanche Breakdown

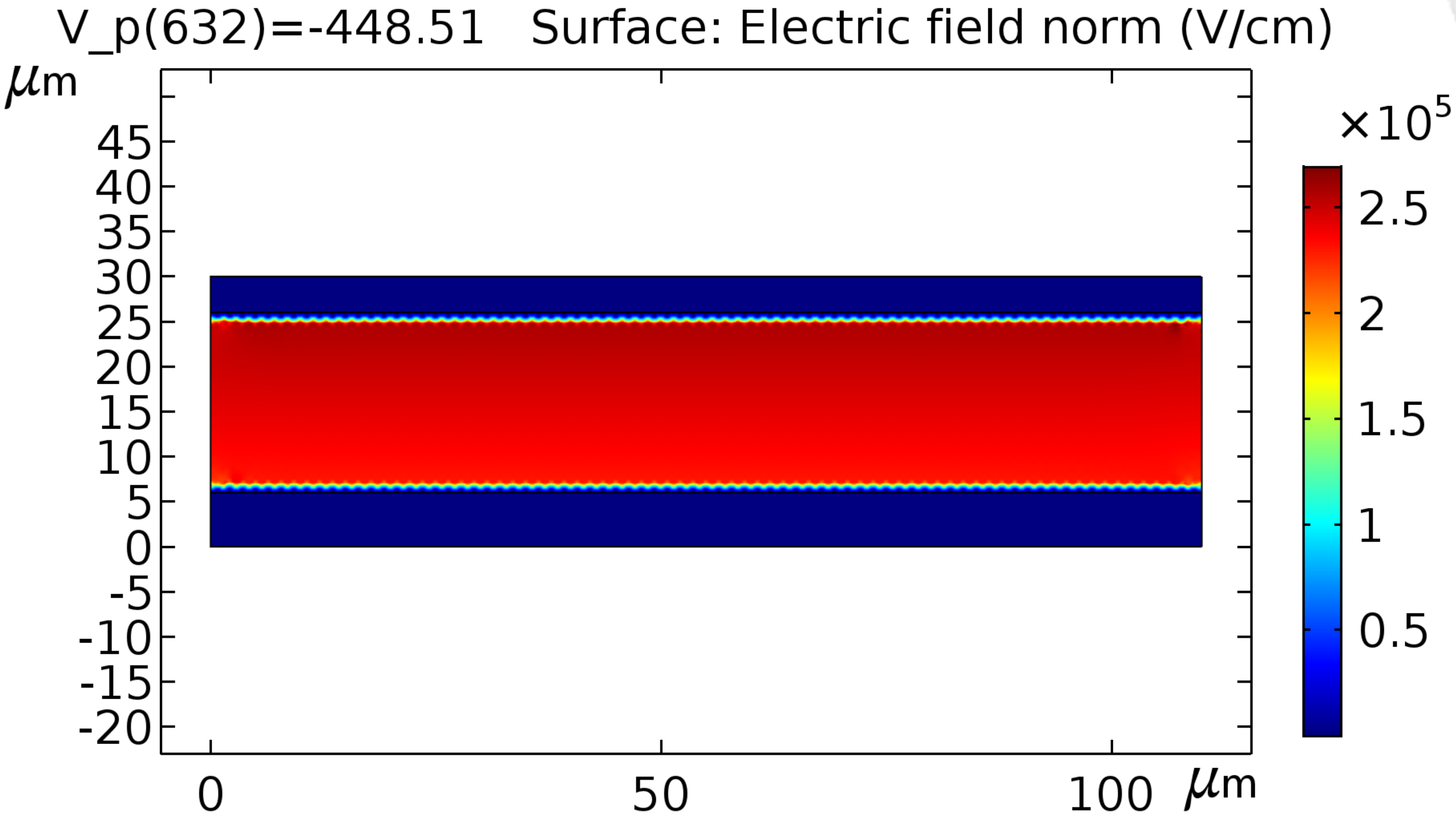


The Planar Junction Diode



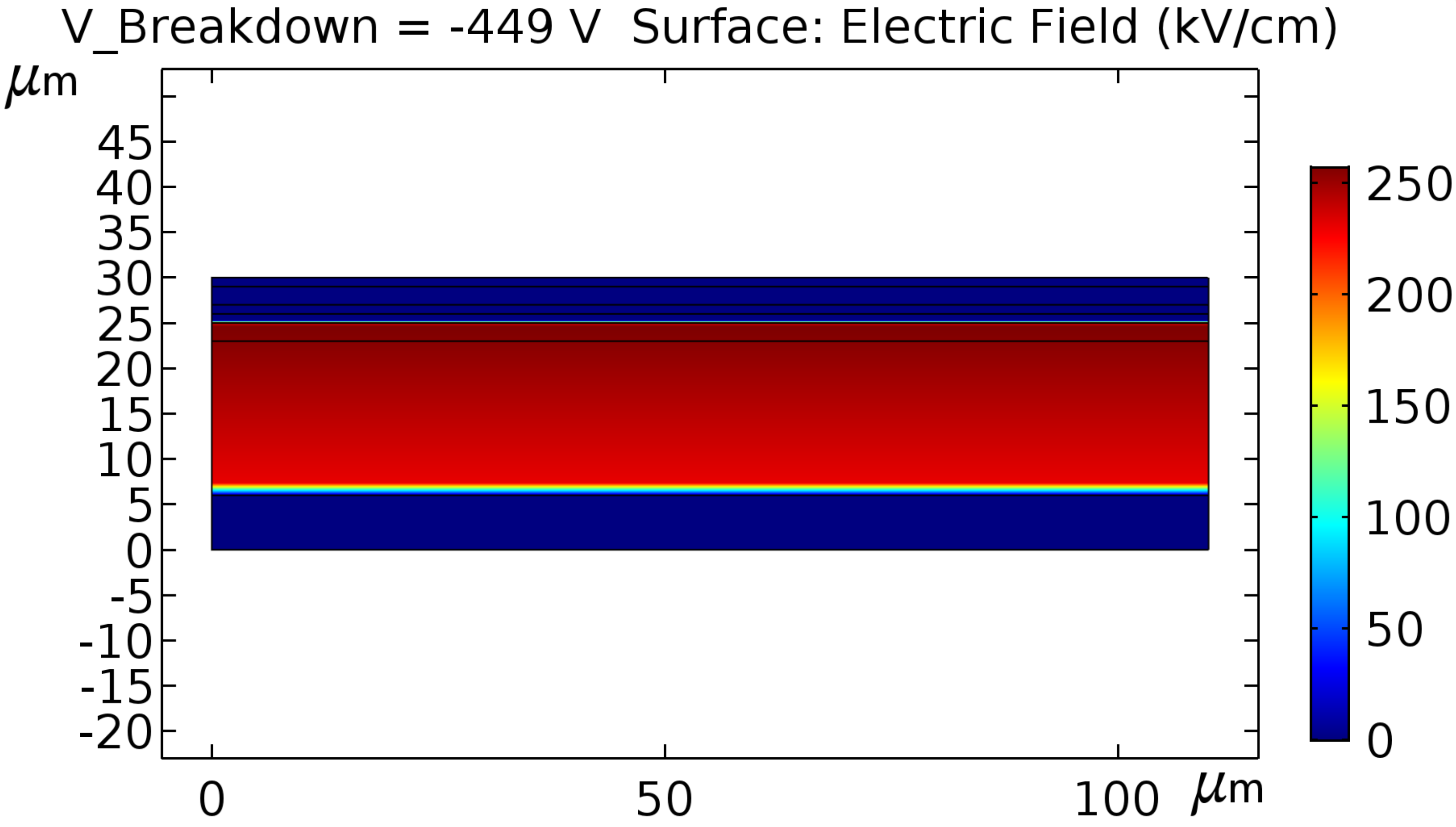
A good starting point is to calculate the planar junction breakdown voltage. This gives the upper limit on the device performance.

Silicon Planar Device



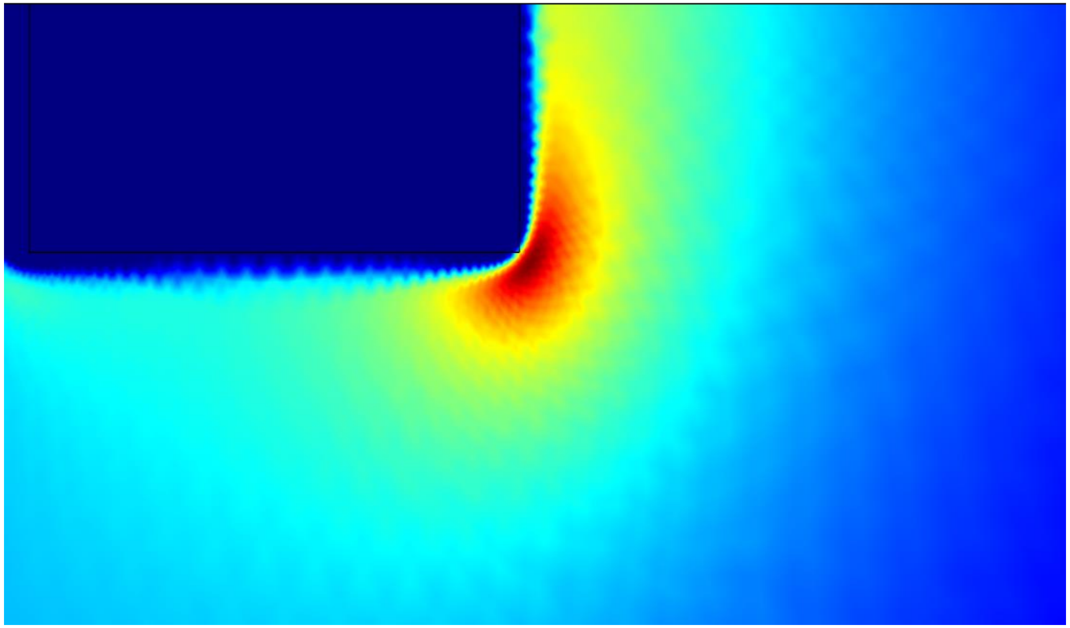
A planar junction devices has a uniform electric field. The wavy line shown is an artifact of the free triangular mesh used. For a 1e14 cm^{-3} doped 20 um thick drift region the simulation fails to converge at -448.5 V which is the device breakdown voltage.

Silicon Planar Device

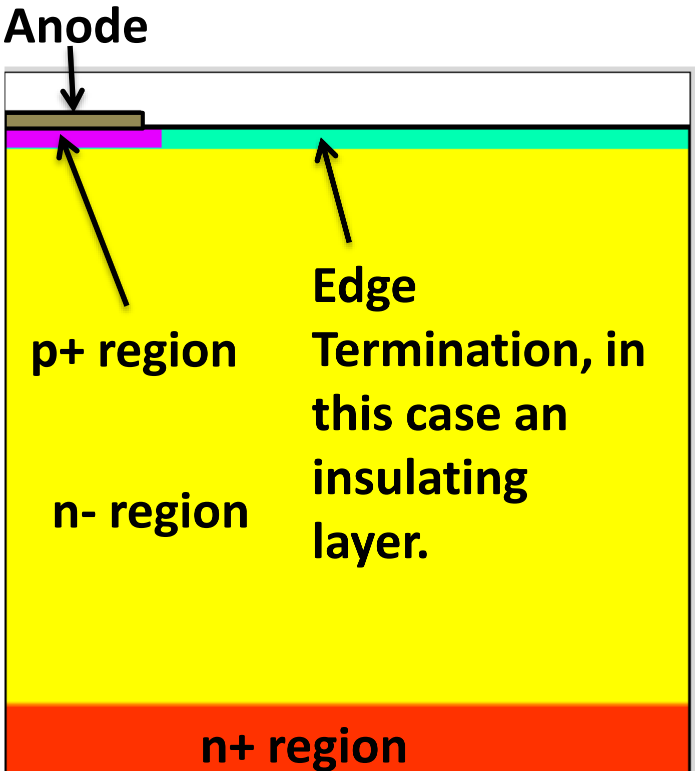


Switching to an Free Quad Mesh removed the wavy field edges and the simulation fails to converge at -449 V.

Edge Termination



The electric field crowding effect is seen on sharp corners of doping profiles. This leads to premature breakdown in devices.



Physically realizable devices cannot have infinite parallel planes.

Edge Termination Schemes

Lots of ideas have been suggested to manage field crowding effects:

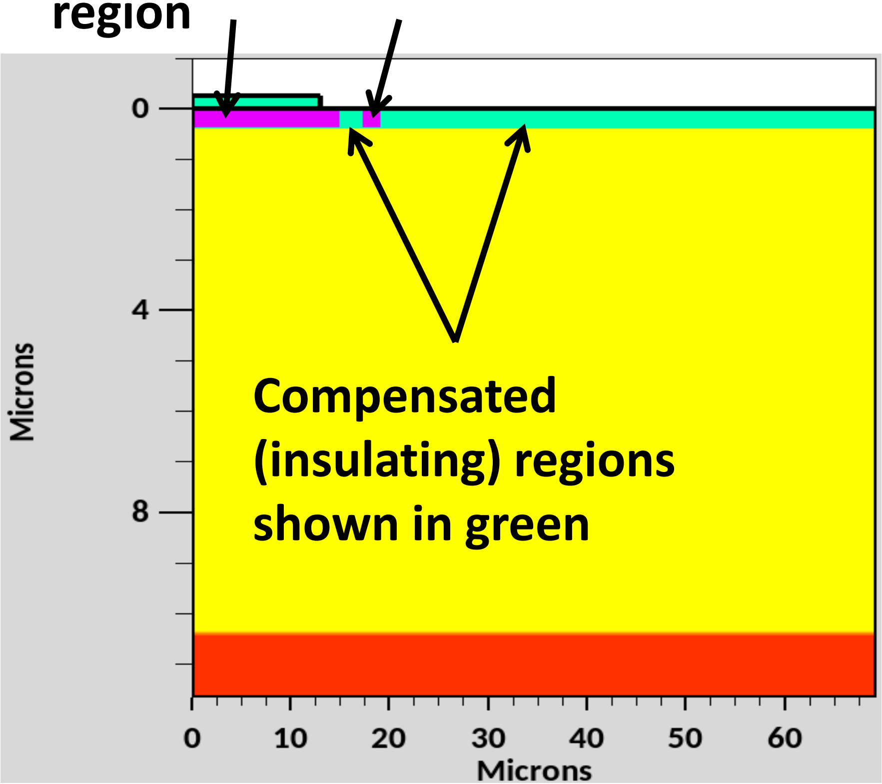
- **Guard rings**
- **Field plates**
- **Beveled surfaces**
- **Etch contours**
- **Junction termination extensions**

B. Jayant Baliga, “*High-voltage device termination techniques a comparative review*” IEE Proceedings I (Solid-State and Electron Devices), Volume 129, Issue 5, October 1982, p. 173 – 179

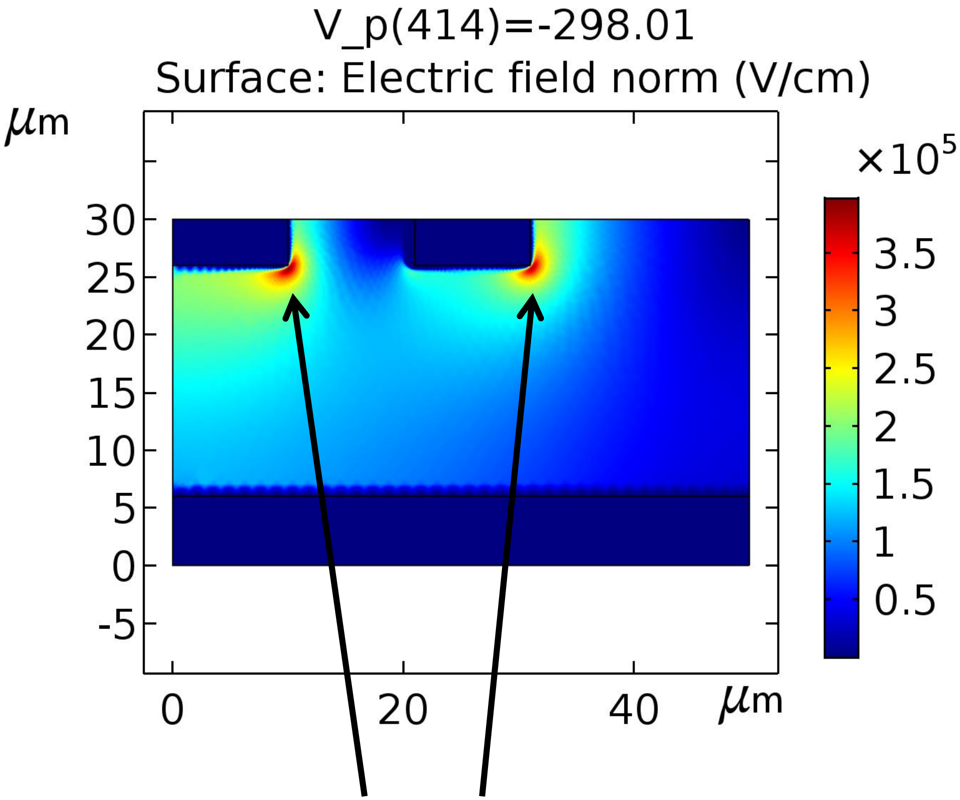
Guard Rings

P+ contact region

P+ guard ring

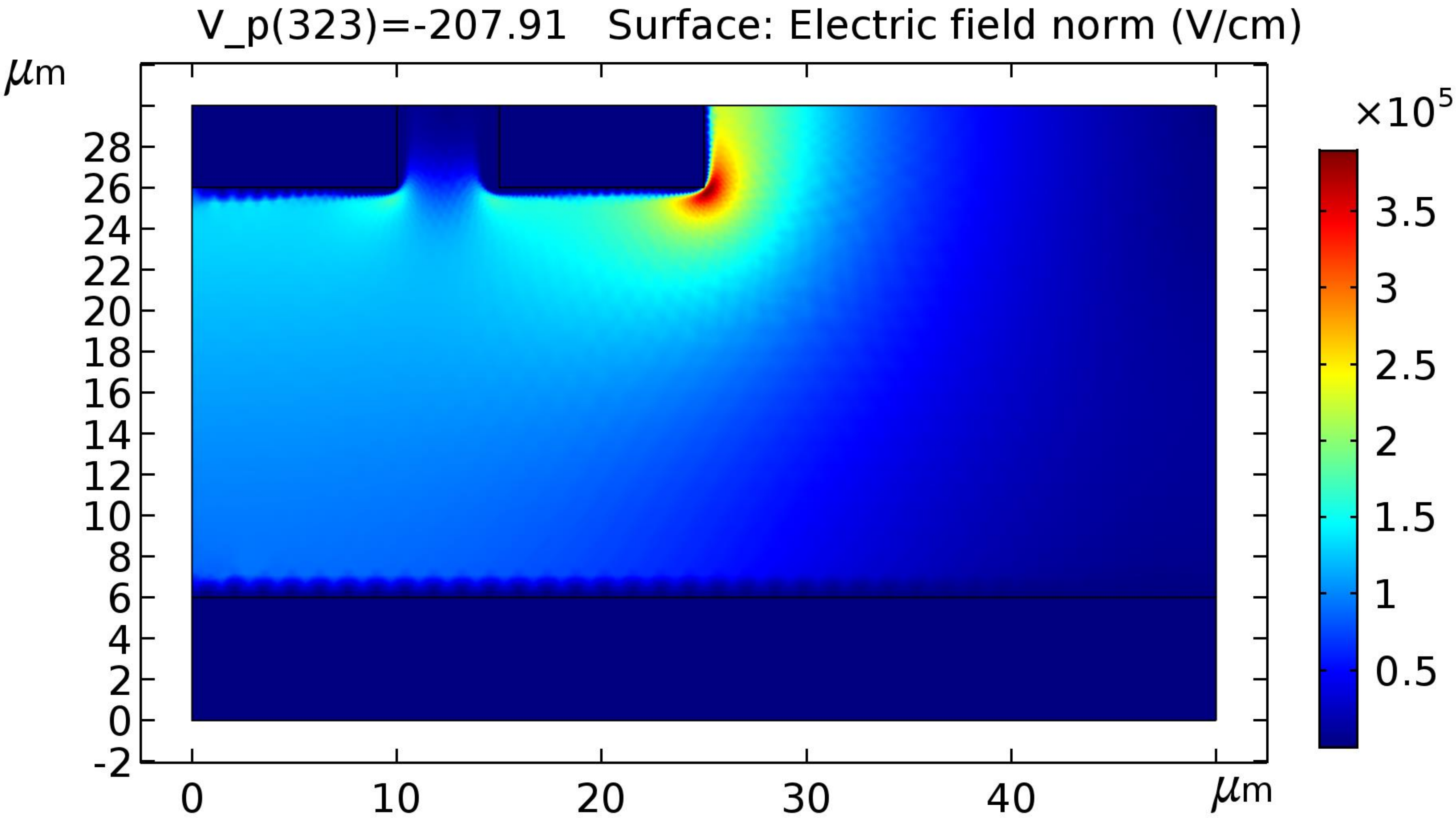


Compensated (insulating) regions shown in green

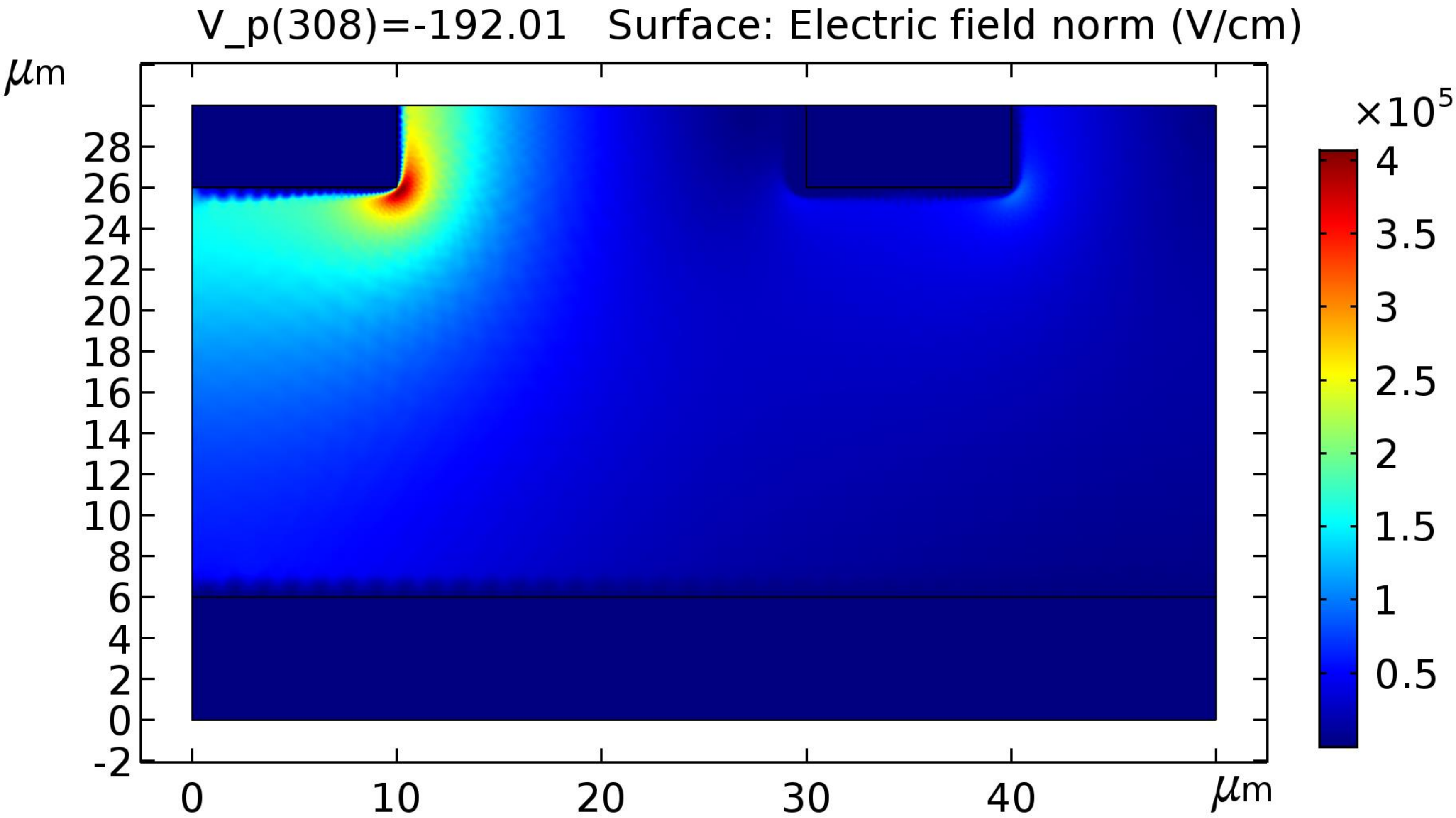


The electric field spreads to the guard ring

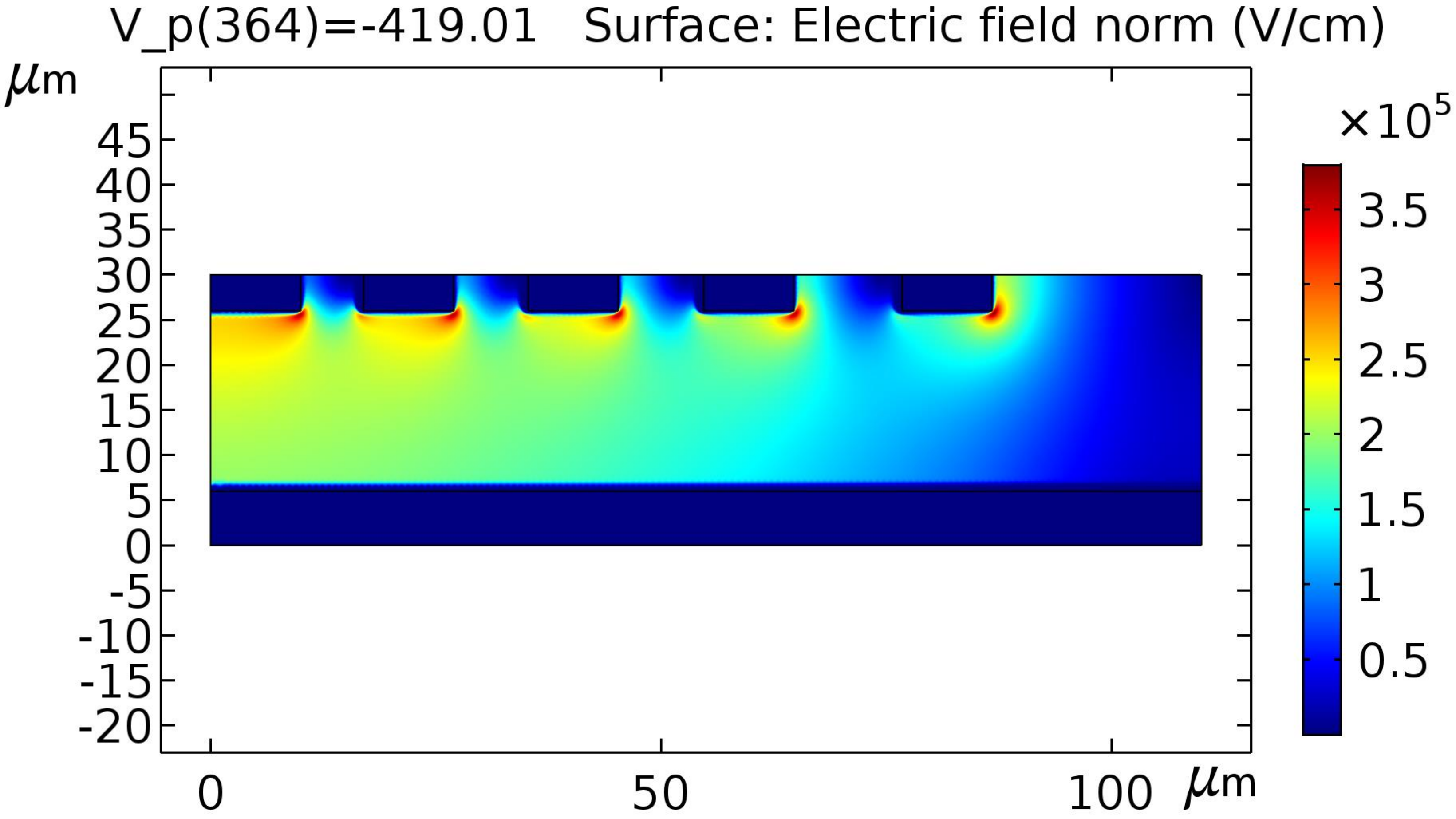
Importance of the guard ring spacing



Importance of the guard ring spacing



4 Guard Rings



Converting to GaN

- Need to add carrier lifetimes and mobilities
- Need to refine the stepsize of the voltage sweep. While 1 V steps worked for the Silicon devices, 0.05 V led to good convergence in GaN.
- Changed the drift region doping from 1e14 cm^{-3} in Si to 2e16 cm^{-3} in GaN. Lower is better for breakdown, however obtaining low doping in GaN is challenging.
- Need to change the impact ionization model parameters.

Converting to GaN

- **Most importantly you need to change the impact ionization model.**

$$\nabla \cdot \mathbf{J}_n += qR_n\,, \quad \nabla \cdot \mathbf{J}_p += -qR_p$$

$$R_n = R_p = -G_n\,, \quad G_n = \left(\alpha_n \frac{|\mathbf{J}_n|}{q} + \alpha_p \frac{|\mathbf{J}_p|}{q}\right) = G_p$$

$$\alpha_n = a_n\left(1 + c_n(T - T_{ref})\right) E_{||,n} \exp\left(-\left(\frac{b_n\left(1 + d_n(T - T_{ref})\right)}{E_{||,n}}\right)^2\right)$$

$$\alpha_p = a_p\left(1 + c_p(T - T_{ref})\right) E_{||,p} \exp\left(-\left(\frac{b_p\left(1 + d_p(T - T_{ref})\right)}{E_{||,p}}\right)^2\right)$$

Okuto Crowell Model (from COMSOL interface)

Converting to GaN

$$\nabla \cdot \mathbf{J}_n + = qR_n \,, \quad \nabla \cdot \mathbf{J}_p + = -qR_p$$

$$R_n = R_p = -G_n \,, \quad G_n = \left(\alpha_n \frac{|\mathbf{J}_n|}{q} + \alpha_p \frac{|\mathbf{J}_p|}{q} \right) = G_p$$

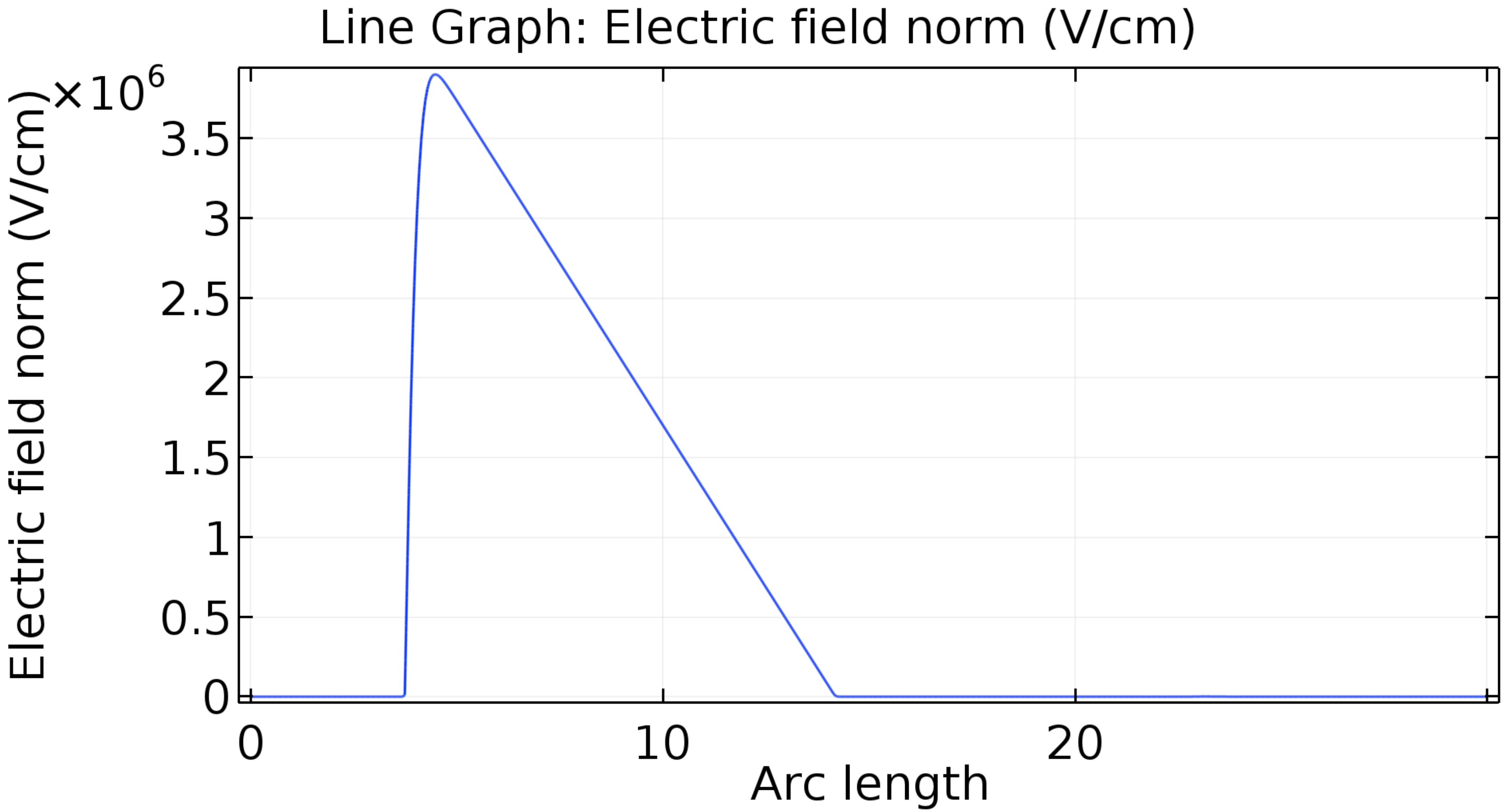
$$\alpha_n = a_n \left(1 + c_n(T - T_{ref})\right) E_{||,n} \exp\left(-\left(\frac{b_n \left(1 + d_n(T - T_{ref})\right)}{E_{||,n}} \right)^2 \right)$$

$$\alpha_p = a_p \left(1 + c_p(T - T_{ref})\right) E_{||,p} \exp\left(-\left(\frac{b_p \left(1 + d_p(T - T_{ref})\right)}{E_{||,p}} \right)^2 \right)$$

Si: an = 0.426; ap = 0.243; bn = 4.81e5; bp=6.53e5; etc (default)
Si critical electic field ~350 kV/cm

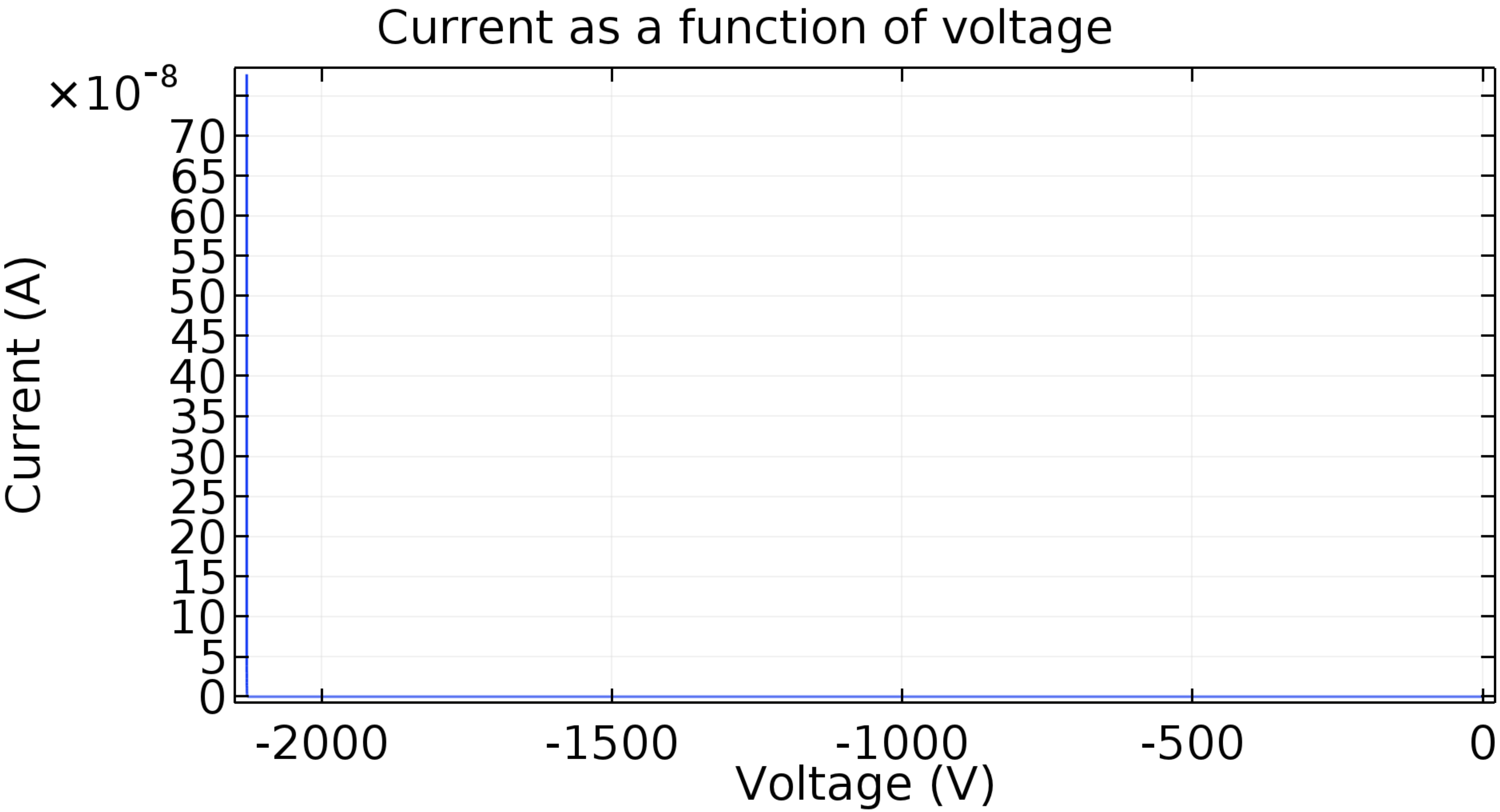
GaN: an=ap=4.3; bn=bp=1.05e7; cn=cp=dn=dp=0 (ignore temperature dependence)
GaN critical electric field ~4.0 MV/cm
These GaN numbers are calculated to achieve a 4 MV/cm critical electric field.
They are not from literature, empirical data, and have not been validated!

GaN Planar Electric Field at Breakdown



A cutline of the electric field profile shows we are indeed approaching 4 MV/cm at breakdown. The profile also indicates the depletion depth is only 10 um. The high doping of 2e16 means that a 20 um drift region is twice as thick as we need.

GaN Reverse Bias Current-Voltage



The breakdown of this device is over 2100 V!

Precision is KEY!

“The convergence and accuracy of a device simulation requires the numerical resolution of the quantities (n-p) and (n+p). The first of these quantities appears in the space charge density… while the second is used implicitly in the calculation of current conservation.”

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Law of Mass Action:

$$n_i * n_i = n * p$$

$$n_i = \sqrt{N_v N_c} e^{(-E_g/2kT)}$$

$$n_{i\_Si} \approx 10^{10}$$

n=1e18, p=100

$$n_{i\_GaN} \approx 10^{-10}$$

n=1e18, p=1e-28

$$n_{i\_AlN} \approx 10^{-34}$$

n=1e18, p=1e-86

Precision is KEY!

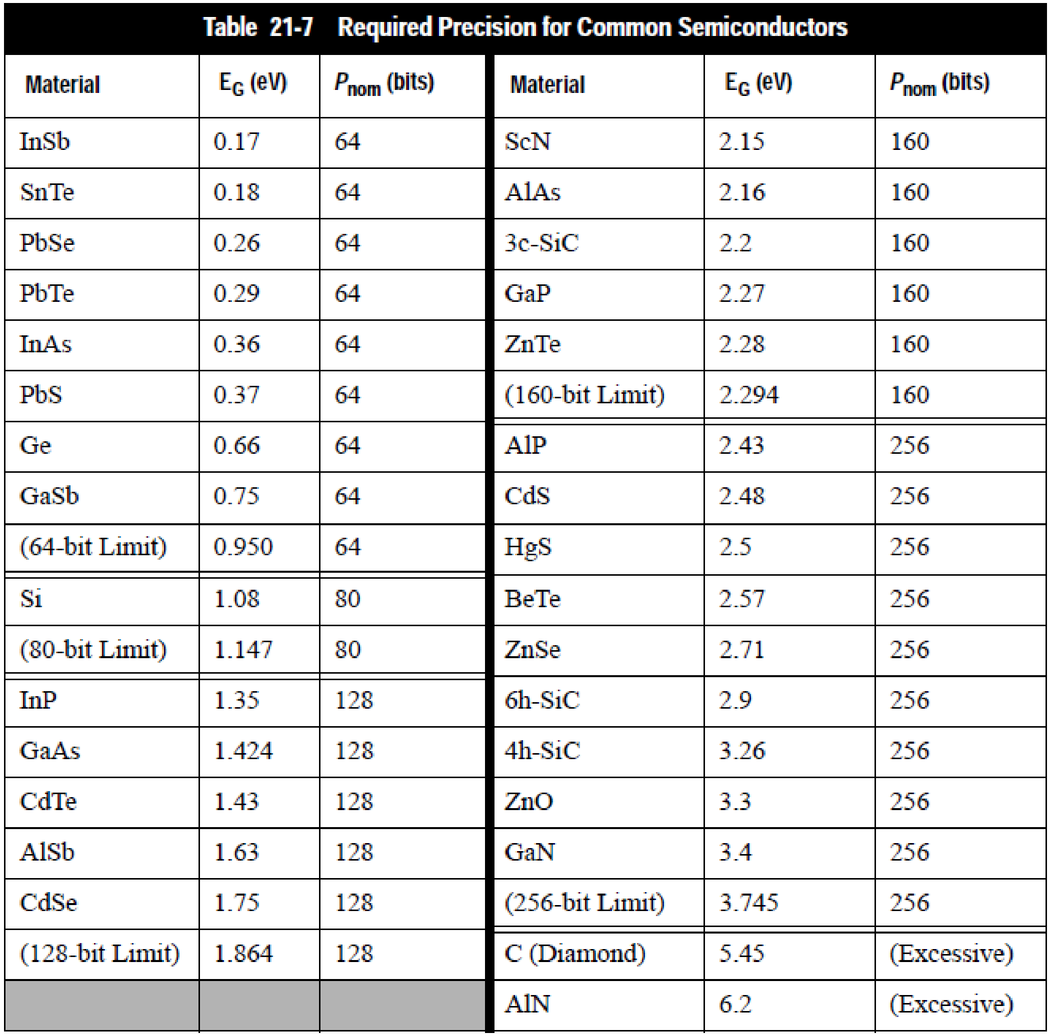

Table 21-7 Required Precision for Common Semiconductors

Material	E_G (eV)	P_{nom} (bits)	Material	E_G (eV)	P_{nom} (bits)
InSb	0.17	64	ScN	2.15	160
SnTe	0.18	64	AlAs	2.16	160
PbSe	0.26	64	3c-SiC	2.2	160
PbTe	0.29	64	GaP	2.27	160
InAs	0.36	64	ZnTe	2.28	160
PbS	0.37	64	(160-bit Limit)	2.294	160
Ge	0.66	64	AlP	2.43	256
GaSb	0.75	64	CdS	2.48	256
(64-bit Limit)	0.950	64	HgS	2.5	256
Si	1.08	80	BeTe	2.57	256
(80-bit Limit)	1.147	80	ZnSe	2.71	256
InP	1.35	128	6h-SiC	2.9	256
GaAs	1.424	128	4h-SiC	3.26	256
CdTe	1.43	128	ZnO	3.3	256
AlSb	1.63	128	GaN	3.4	256
CdSe	1.75	128	(256-bit Limit)	3.745	256
(128-bit Limit)	1.864	128	C (Diamond)	5.45	(Excessive)
			AlN	6.2	(Excessive)

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Conclusion

- **COMSOL simulations seem to accurately calculate breakdown in simple 2D structures for Silicon and for the planar configuration for GaN.**

- **GaN parameters for breakdown are not known for the Okuto Crowell model. Adding other models, such as the simple Shockley model, would allow for empirically calculated values to be used.**

- **Wide bandgap materials, which are gaining lots of attention in the semiconductor community need more precision. This is a plug for COMSOL to add some more ☺.**

- **n+p=1000000000000000000.000000000000000000000000001**