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Ultrawide Bandgap Semiconductors: Influence of Material Properties on Power Device Performance

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Stanford: Srabanti Chowdhury

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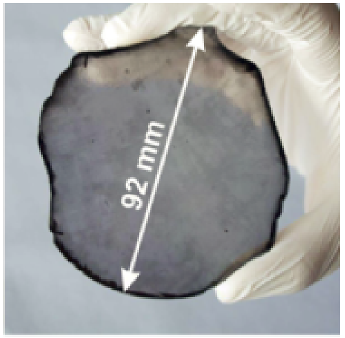
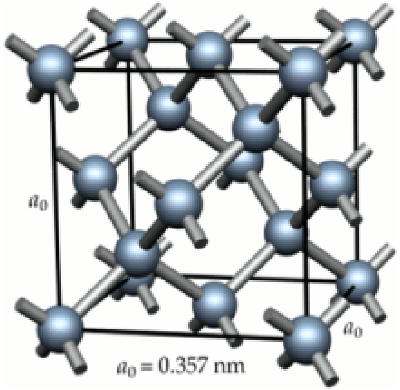
ULTRA Semiconductors



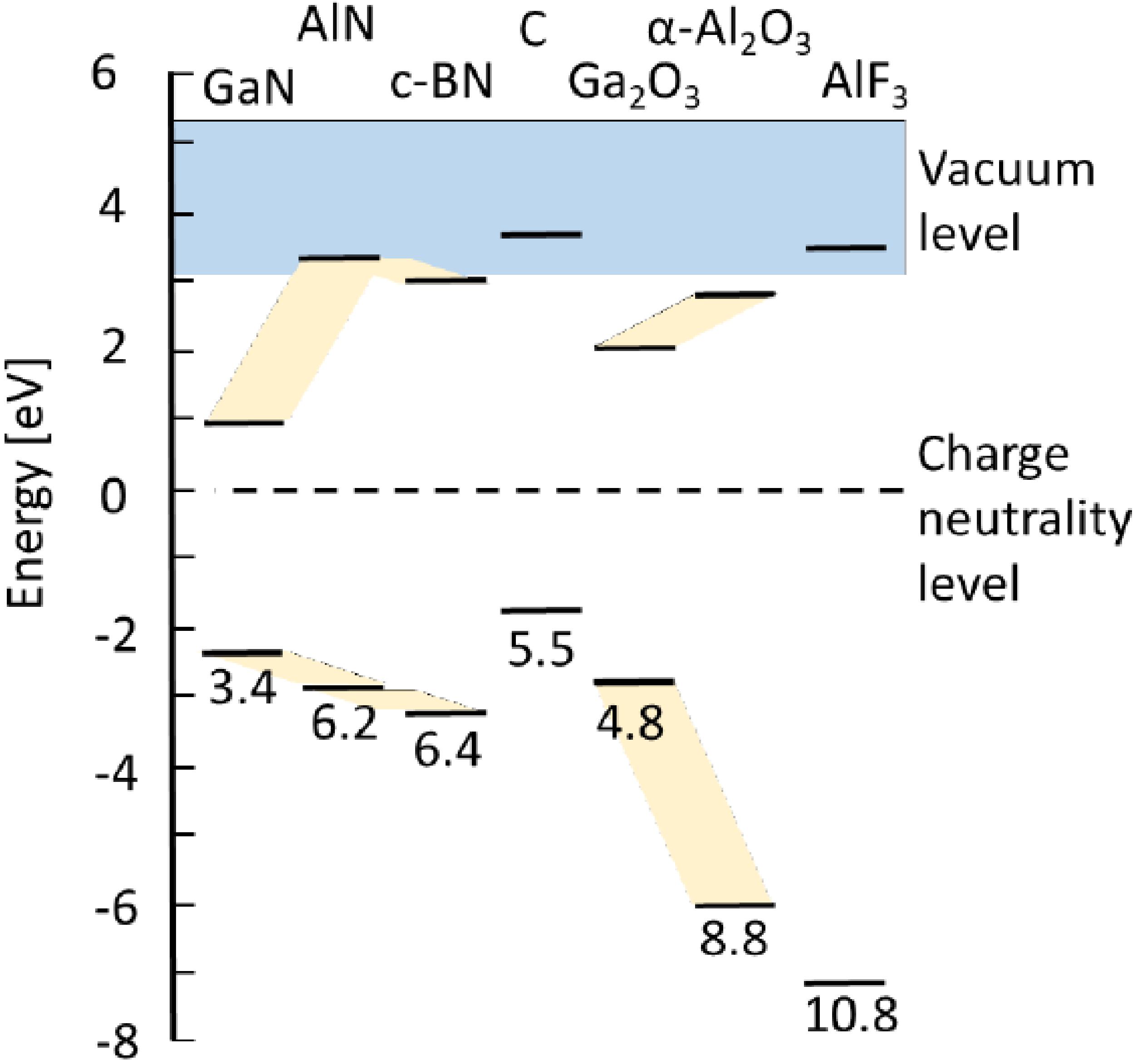
Augsburg Univ.

Diamond Cubic



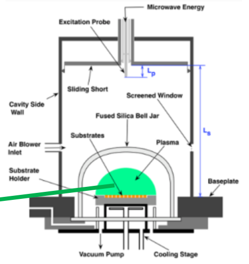
- Eg = 5.5 eV
- sp^3 bonded carbon
- C – 6e
- Diamond Cubic

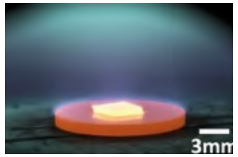
  a = 3.57 Å



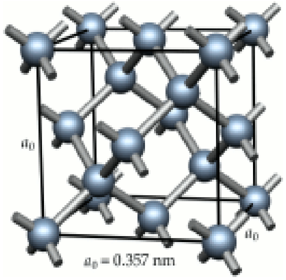
exaTech

G. L. Doll, J. A. Sell, C. A. Taylor II, and R. Clarke, Phys. Rev. B, **43**, 6816 (1991).

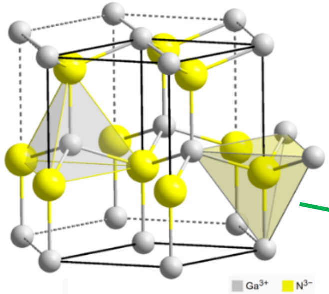




MPCVD

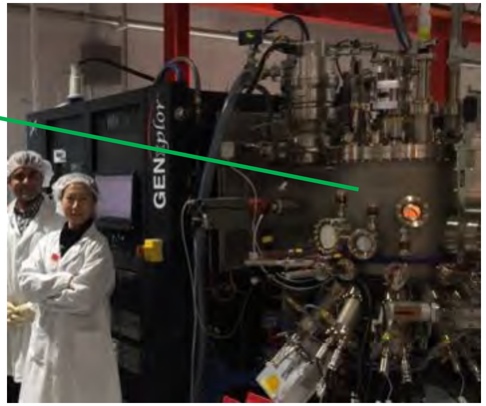


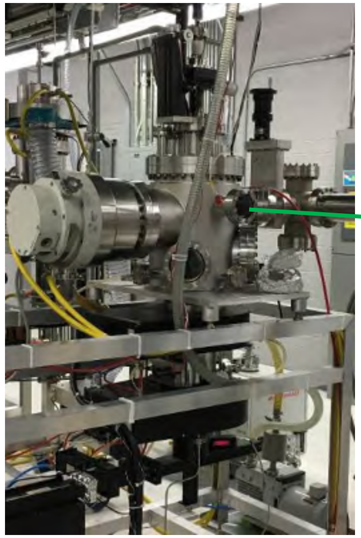
Diamond

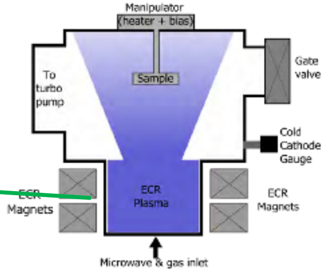


AlN and ($B_xAl_{1-x}N$)

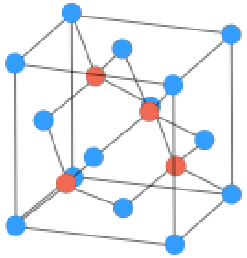
MBE



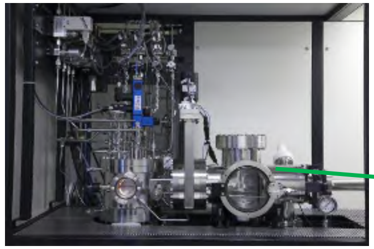




ECR-MPCVD



c-BN

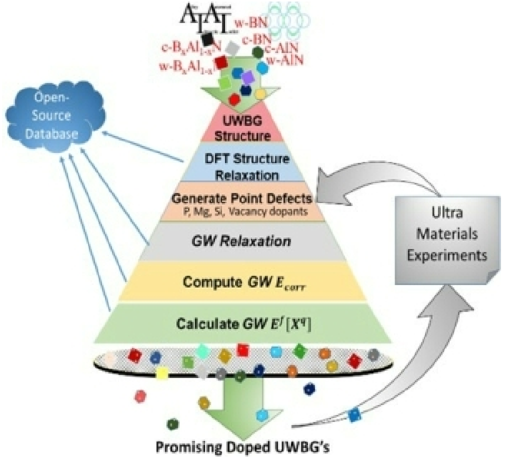


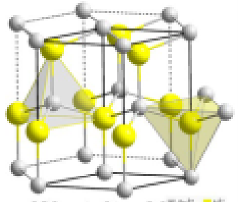
AlGaN

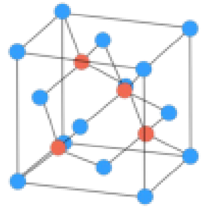
MOCVD

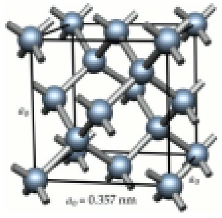
ULTRA EFRC

Mission: To achieve extreme electrical properties and phenomena through fundamental understanding of ultra wide bandgap materials, which will enable a resilient, smart electricity grid.

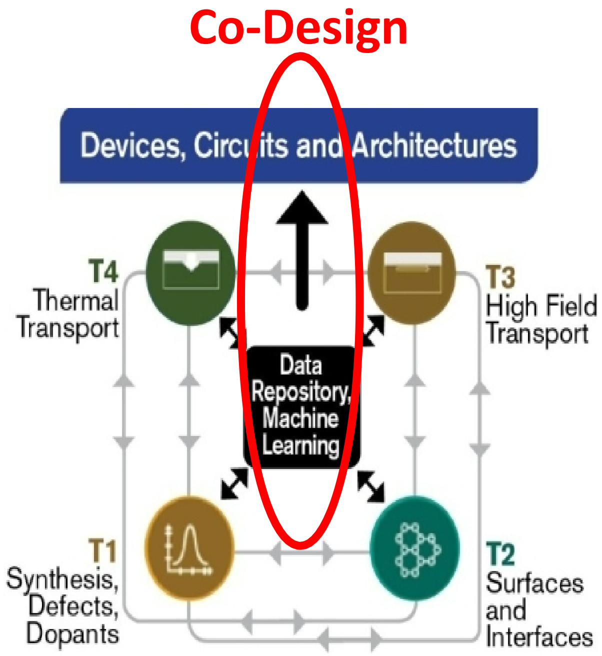



Wurtzite AlN


Cubic boron nitride (c-BN)


Diamond Cubic

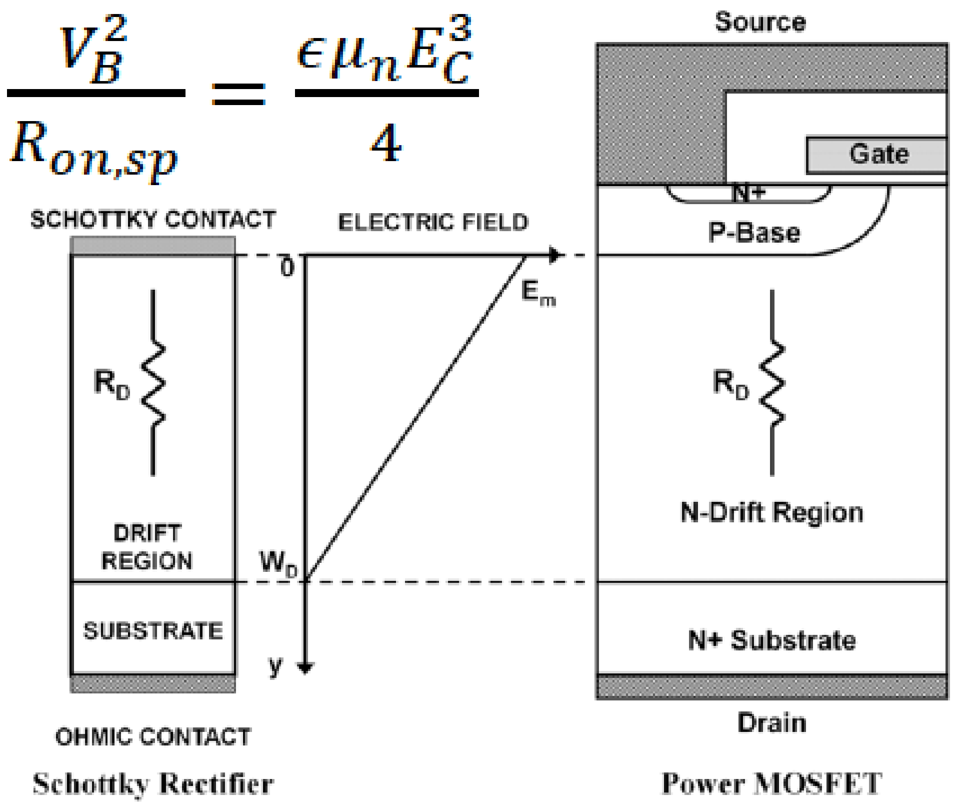
- Methodology
  - ➢ Close integration of theory and computational methods throughout
  - ➢ Materials synthesis, defect and impurity physics
  - ➢ Interfaces, atomic scale and electronic states characterization
  - ➢ High field electronic transport and breakdown characterization
  - ➢ Thermal transport theory and measurement
- Future Grid Co-Design Ecosystem
  - ➢ Provides a knowledge base enabling communication across all levels of the technology

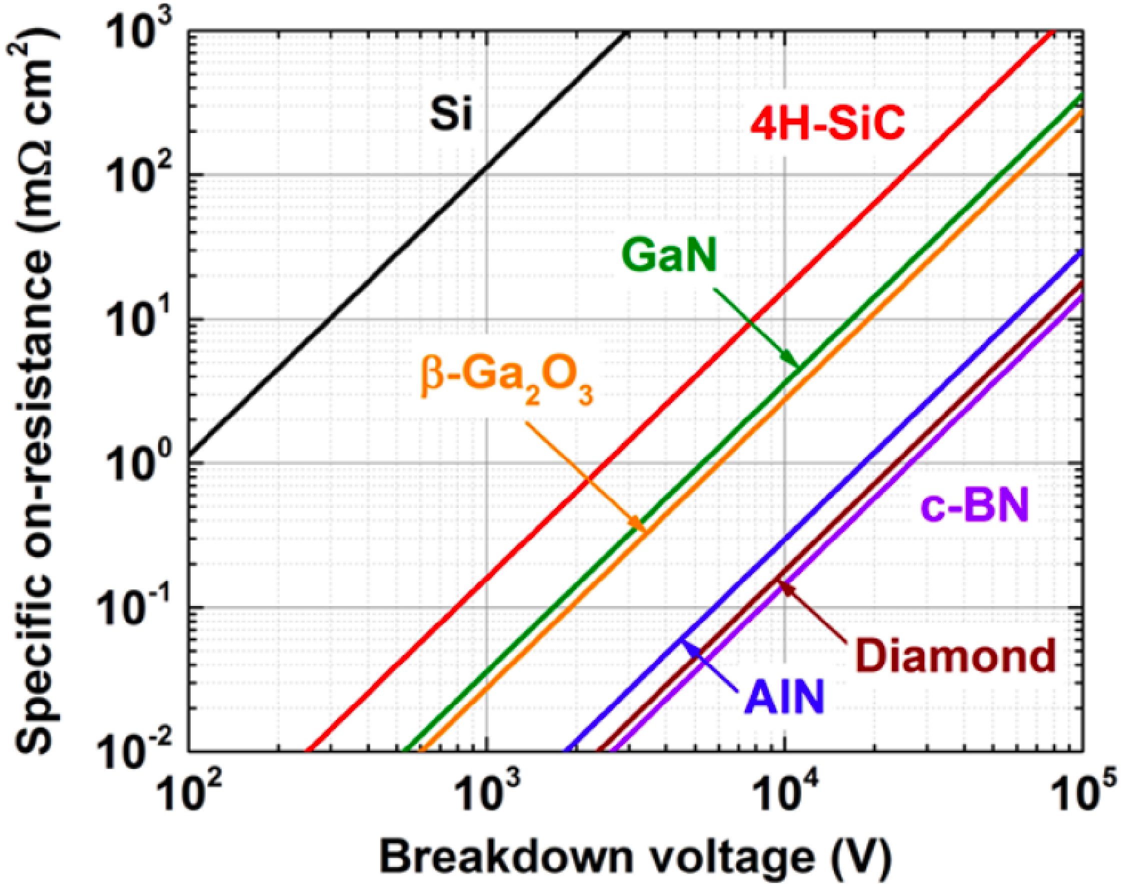


Impact on Power Electronics: Baliga* Figure of Merit

There are two main parameters of importance for power electronics, the breakdown voltage (related to the critical field, E_C for impact ionization), and the specific on-resistance

$$\frac{V_B^2}{R_{on,sp}} = \frac{\epsilon \mu_n E_C^3}{4}$$



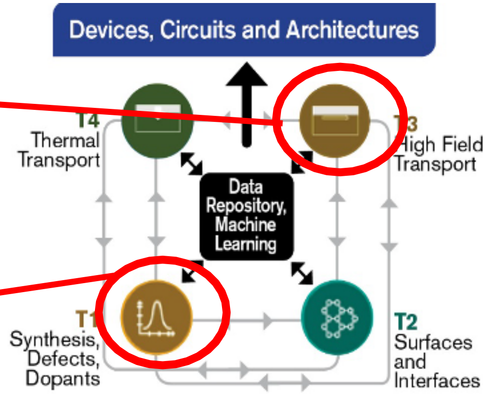


*Baliga B J 1982 Semiconductors for high voltage vertical channel field effect transistors J. Appl. Phys. 53 1759–64

Impact on Power Electronics: Baliga* Figure of Merit

The *unipolar* FOM is widely used to compare materials of power electronic applications, based on two important quantities: the reverse breakdown voltage, V_B, and the forward specific on-resistance, $R_{on,sp}$:

$$FOM = \frac{V_B^2}{R_{on,sp}}$$



For Ohmic conduction, $R_{on,sp}$ is connected to the semiconductor material through the electron (hole) density, $n(p)$, the carrier mobility, $\mu_{n,p}$, and the drift region width, W_d:

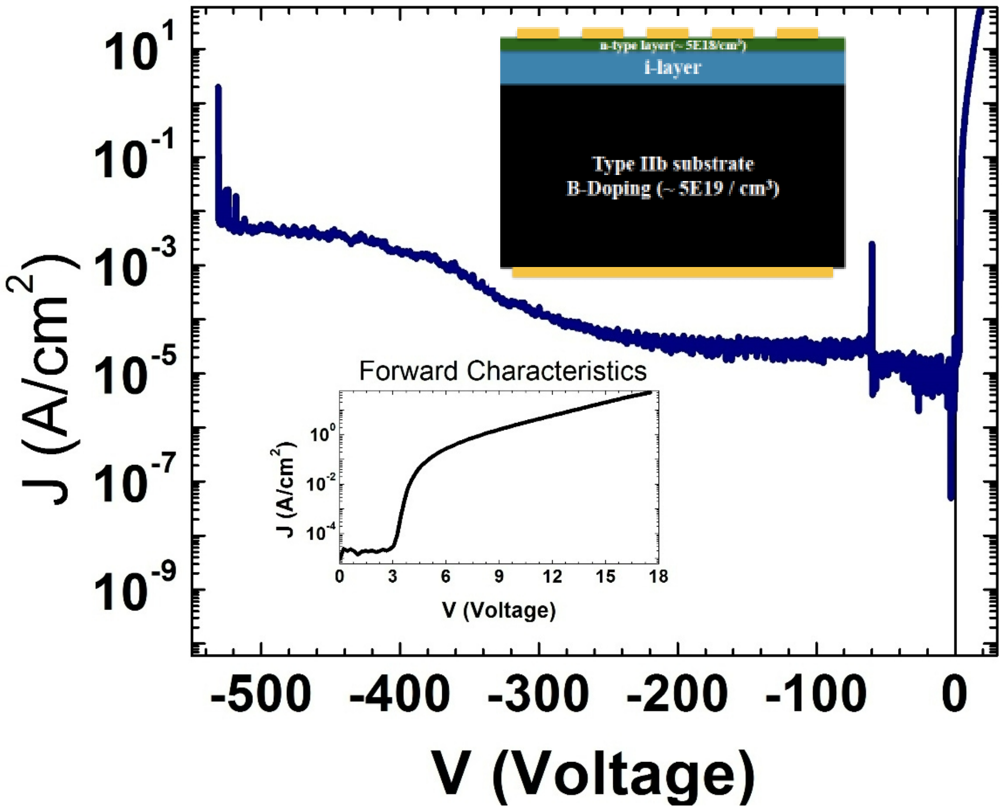
$$R_{on,sp} = \frac{W_d}{q\mu_{n,p}(n,p)}$$

The breakdown voltage depends on the breakdown (critical) field, $V_B = \eta \mathcal{E}_{cr} W_d$, which varies as the square of the bandgap

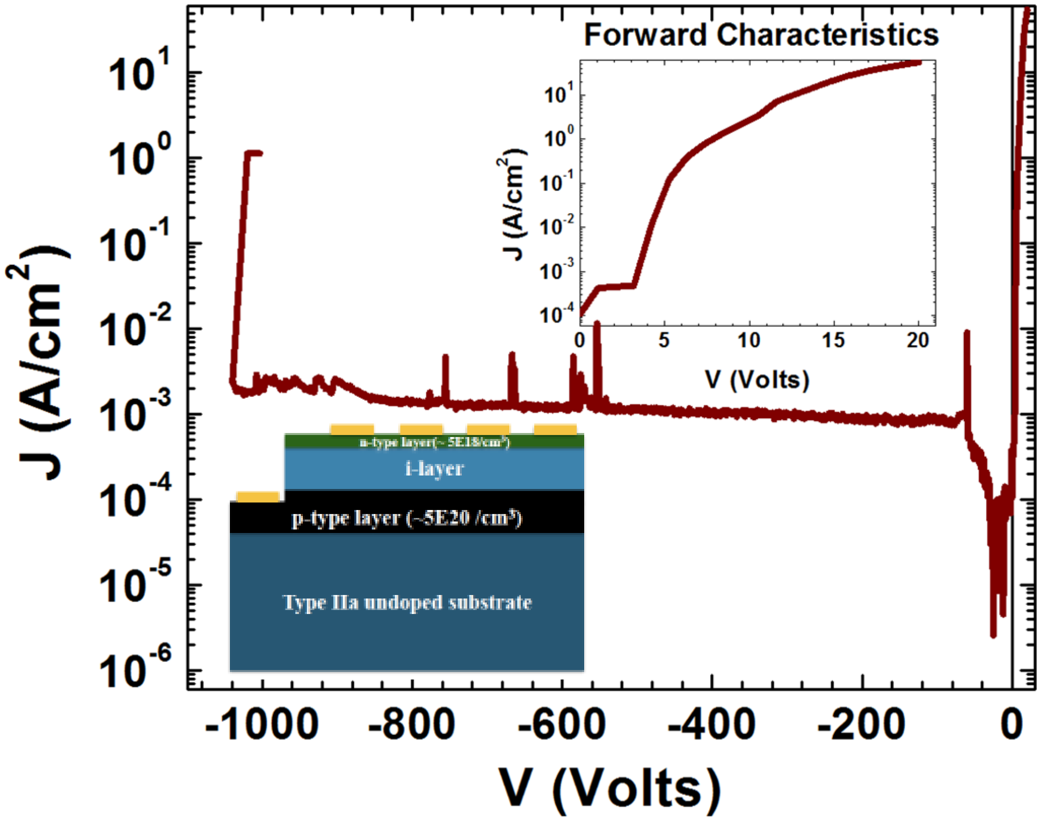
	Narrow	Wide		ULTRAs – New class of materials			
	Si	4H-SiC	GaN	ß-Ga_2O_3	Diamond	h-AlN	h-BN
Bandgap (eV)	1.12	3.26	3.4	4.9	5.5	6.2	6.4
Breakdown Field (MV/cm)	0.3	2.5	3.8	8	10	16	12
Baliga's figure of merit (FOM)	**1**	**183**	**535**	**3444**	**9000**	**9797**	**1678**
	Traditional	New		Emerging Technology			

From M. Kuball, EFRC highlight 2020

Breakdown in Diamond SPIN Diodes



- ❑ Type IIb substrate with ~ 3.5 micron i-layer
- ❑ Forward Current Density ~ 50 A/cm^2 at 17 V
- ❑ Breakdown voltage ~ 530 V at 1E-2 A/cm^2



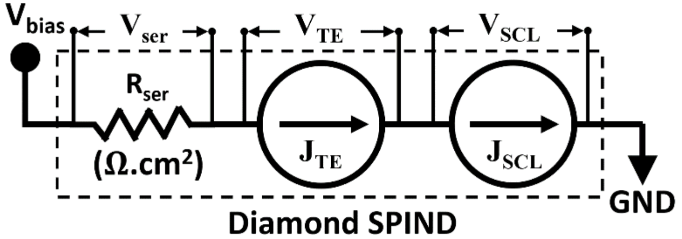
- ❑ Type IIa substrate with ~ 8.5 micron i-layer
- ❑ Forward Current Density ~ 55 A/cm^2 at 20 V
- ❑ Breakdown voltage ~ 1040 V at 1E-3 A/cm^2

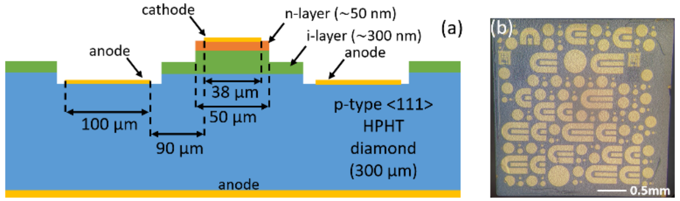
< 10 /

M. Dutta, F. Koeck, R. Hathwar, S. Goodnick, R. Nemanich, and S. Chowdhury, “Demonstration of diamond-based Schottky p-i-n diode with blocking voltage > 500 V,” IEEE Elect Device Lett., 37, 1170 (2016)

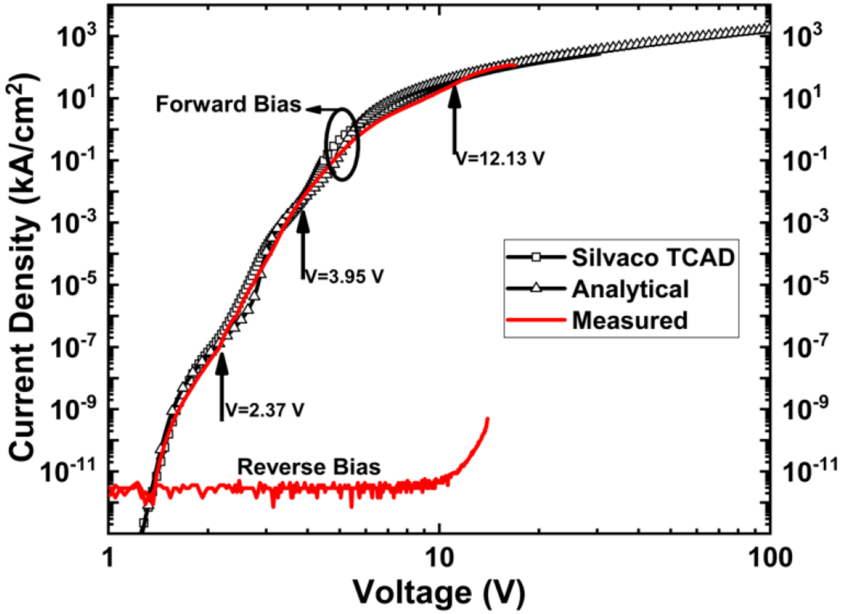
Forward Characteristics of Diamond SPIN Diodes

Record forward current (116 kA/cm²) measured in Schottky PIN diodes. Strong evidence of Mott-Gurney space charge limited current regime in forward bias including trap effects.

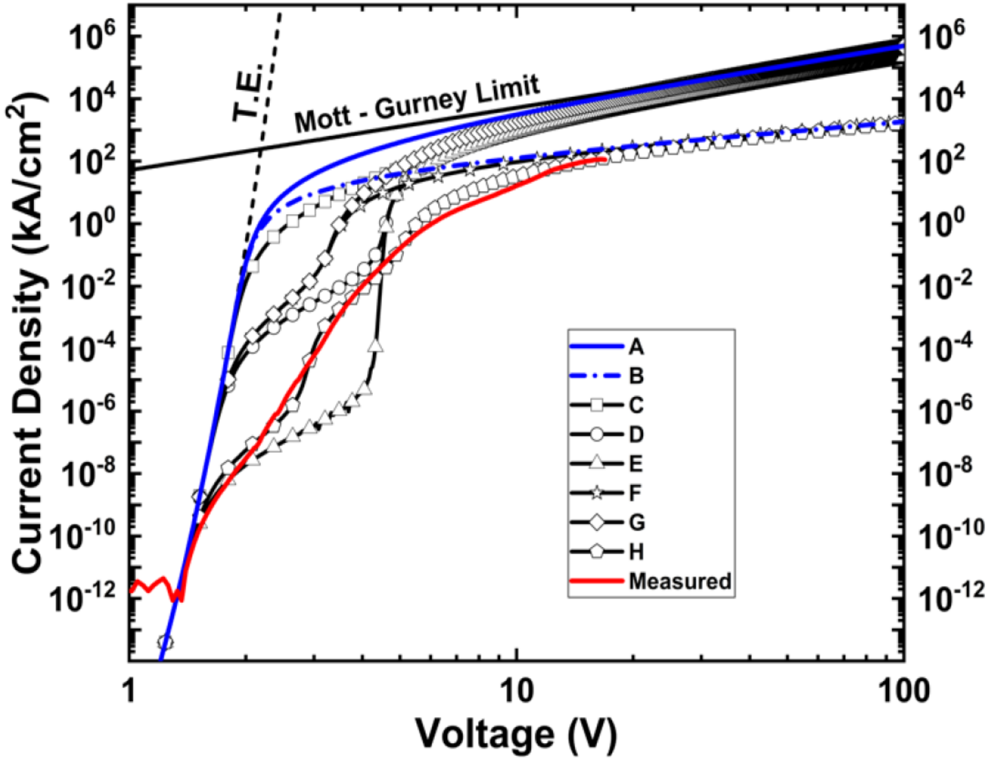




$$J = \frac{9}{8}\epsilon\mu_p\frac{V^2}{d^3}$$

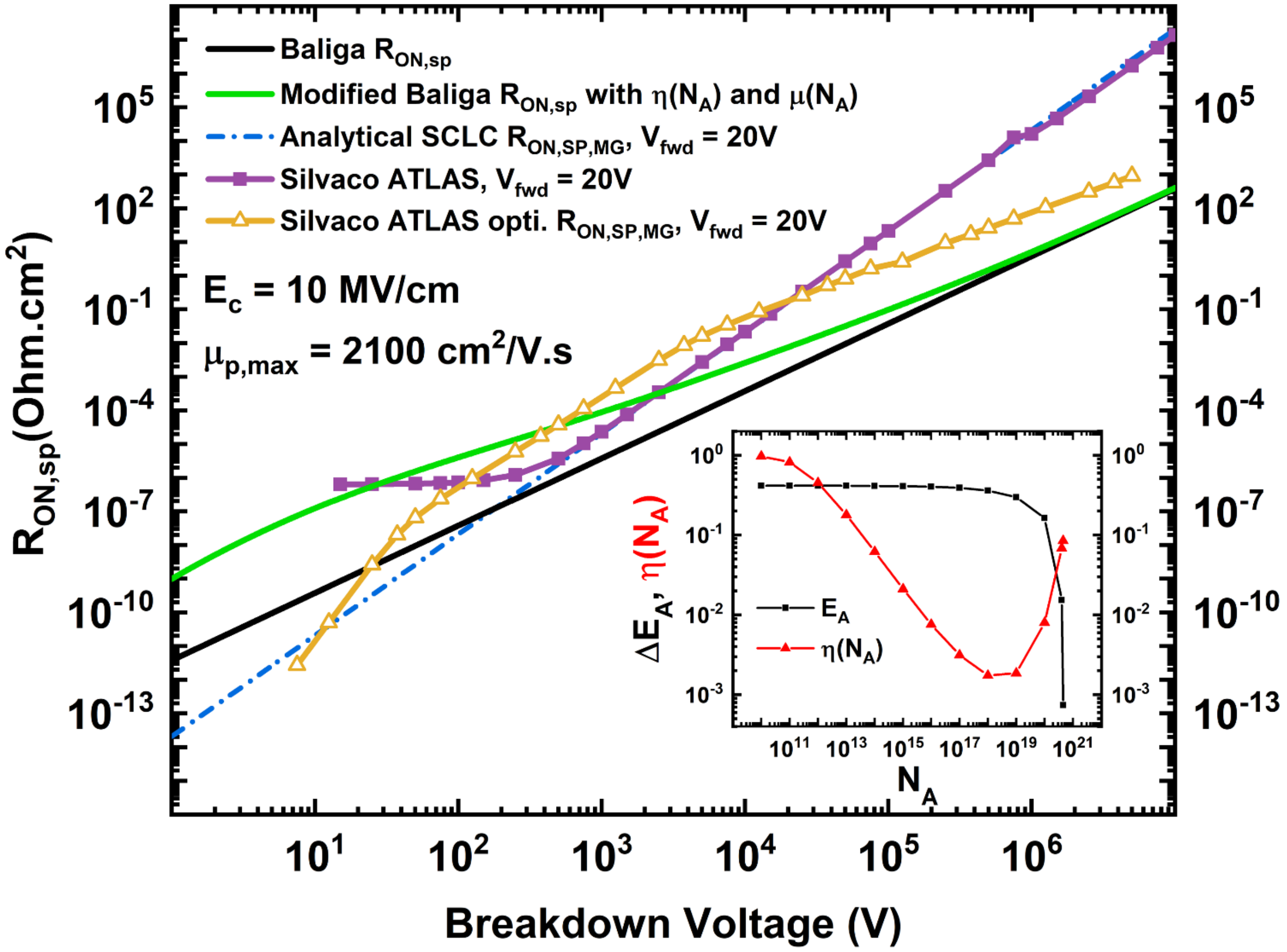


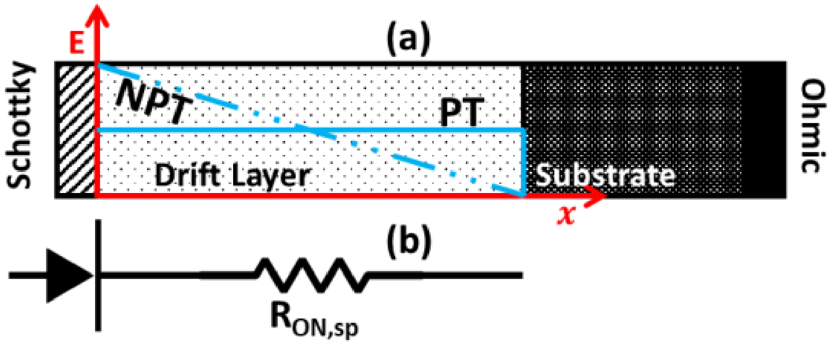
3 Trap model explains jumps in the J-V characteristics, and limitations compared to ideal behavior



H. Surdi, F. A. M. Koeck, M. F. Ahmad, T. J. Thornton, R. J. Nemanich, and S. M. Goodnick, *IEEE Trans. Elec. Dev.* 69(1), 254-261 (2022)

Power Electronic Figure of Merit (FOM) Revisited





Incomplete Ionization

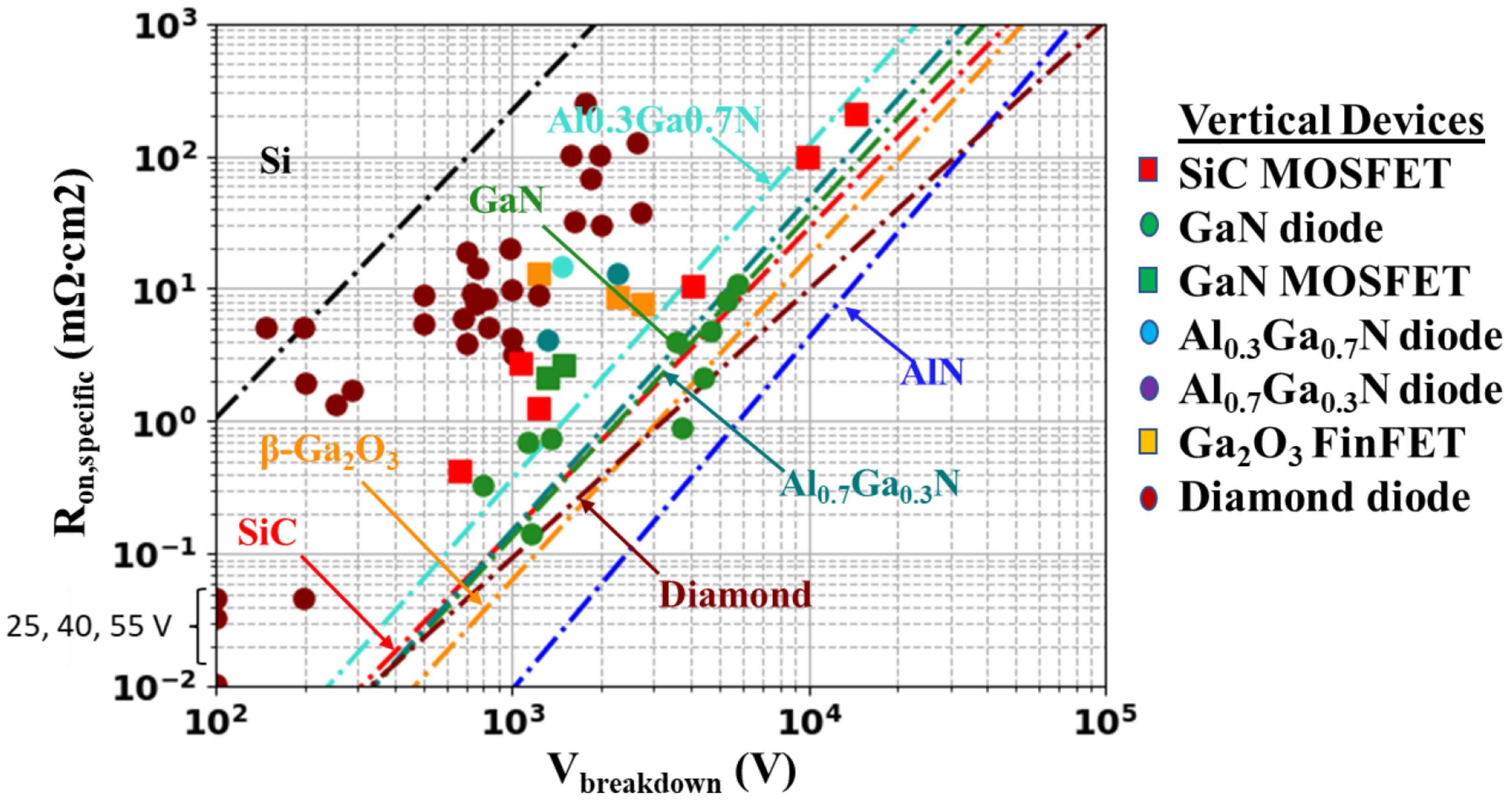
$$R_{ON,sp} = \frac{d}{q\mu(N_A^-)N_A^-}$$

Mott-Gurney

$$R_{ON,sp,MG} = \frac{4}{9\epsilon_r\epsilon_0\mu}\frac{d^3}{V}$$

Note: FOM no longer given by $\frac{V_B^2}{R_{on,sp}}$ for non-Ohmic I-V

Comparison Between Materials and to Experimental



Data points taken from A. J. Green, J. Speck, G. Xing, et al., "β-Gallium Oxide Power Electronics," APL Mater. 10, 029201 (2022), and various other references

Other FOMs Under Investigation

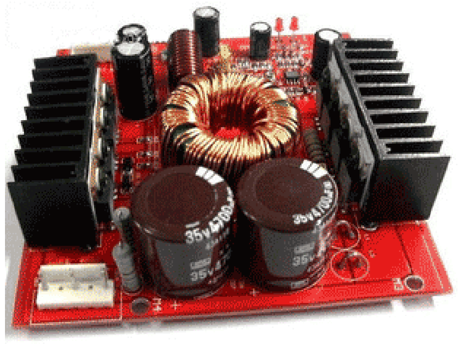
Presently being evaluated!

$$P_{loss,min} = \frac{4I_{rms}(V_B V_D)^{3/4}\sqrt{\frac{kI_D f}{i_{g,av}}}}{E_C\sqrt{\mu}} \Rightarrow \frac{f}{E_C^2\mu} = \text{Constant} \Rightarrow$$

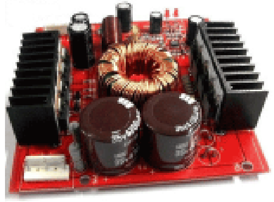
Power Density ~ f

~ $E_C^2\mu$ = $HMFOM^2$

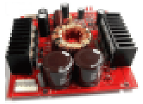
Huang Material Figure of Merit



Si-based converter



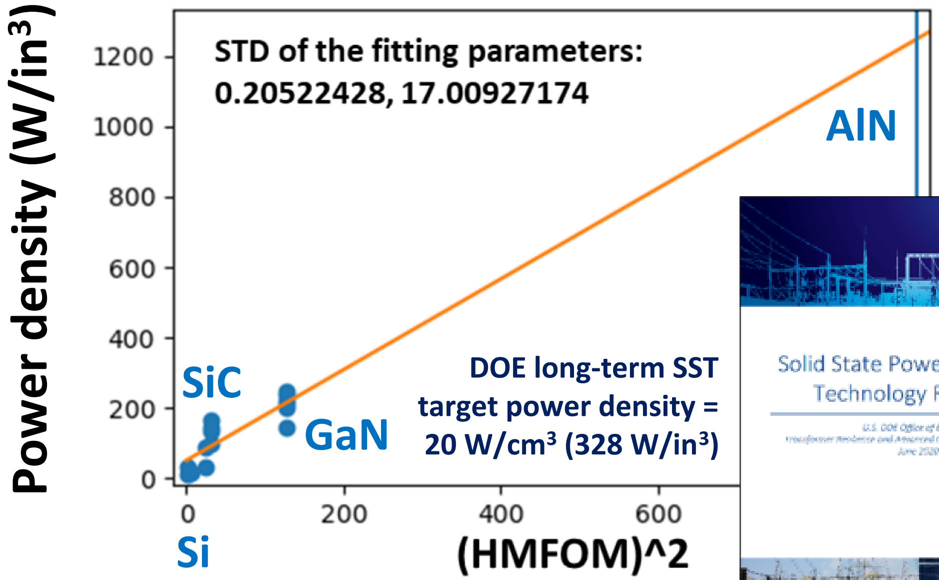
WBG-based converter



UWBG-based converter

Need to also take into account thermal properties – other FOMs are applicable

HMFOM^2 vs Power Density



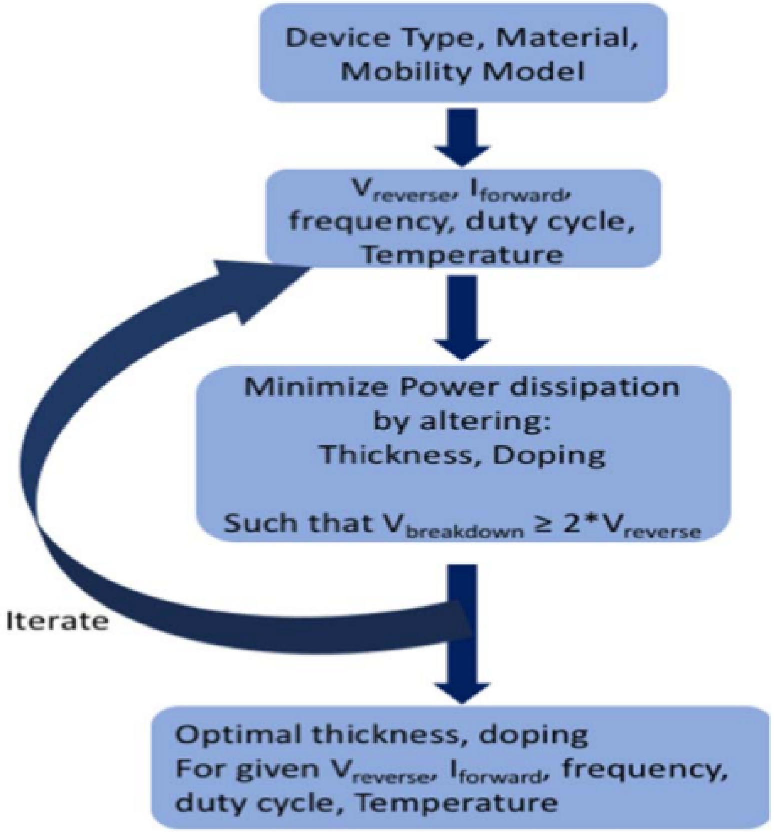
Based on analysis in R. J. Kaplar, J. C. Neely, et al., IEEE Power Electronics Magazine (March 2017) and A. Q. Huang, IEEE Electron Device Letters vol. 25 (May 2004)

PIN and SBD Diode Power Loss Optimization

- For a given set of operating parameters, the doping level and drift thickness are optimized to minimize power loss:

$$P_{total} = P_{forward} + P_{reverse} + P_{dynamic} + P_{displacement}$$

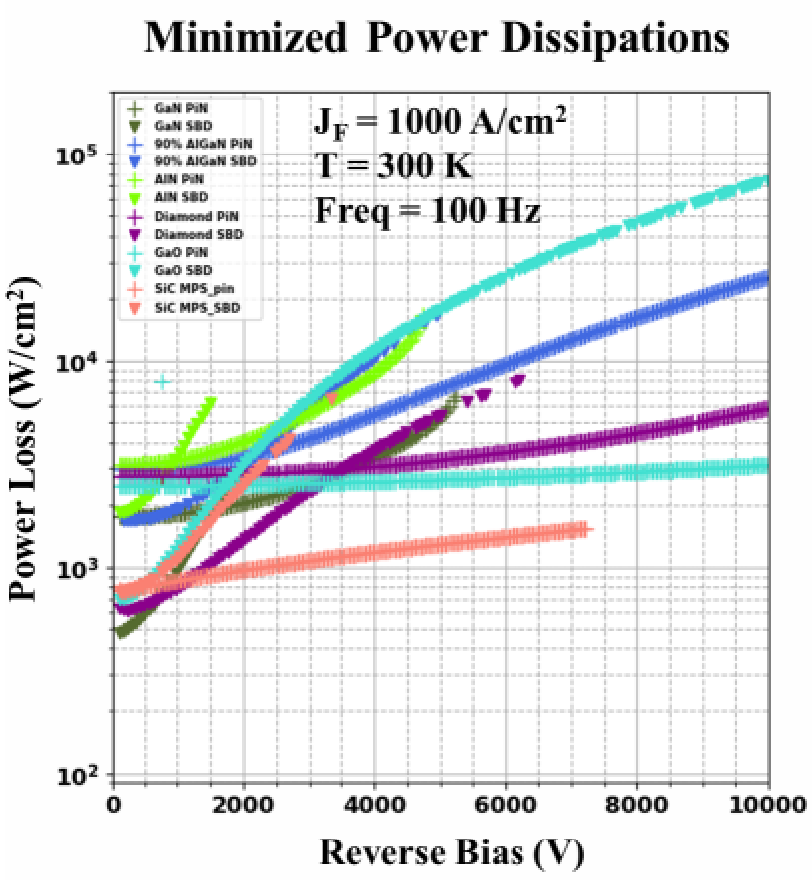
- The temperature- and doping-dependent mobilities are calculated theoretically or with empirical models fit to experiment
- The temperature-, doping-, and drift thickness-dependent critical fields are calculated from the ionization integral*
- UWBG-specific effects such as incomplete ionization and space-charge limited current are included

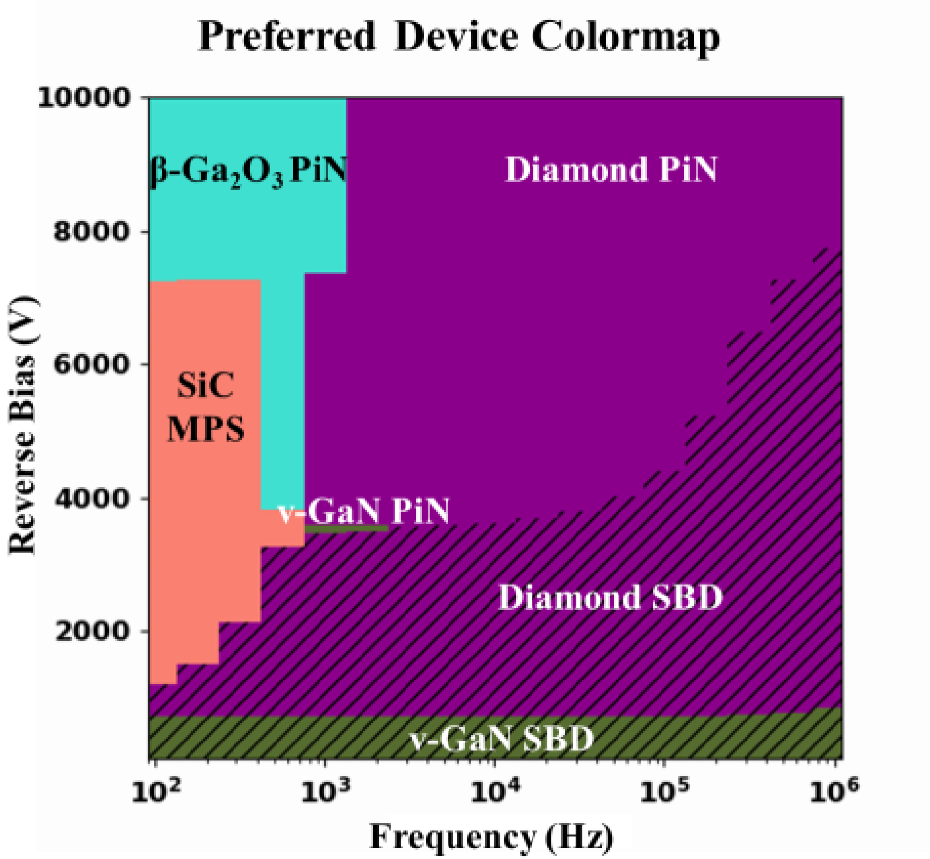


*J. Cooper et al., EDL 41(6) 892 (2020)

PIN and SBD Diode Power Loss Optimization

- **The UWBG material and diode type (PIN or Schottky) that produces the lowest power loss for each reverse bias and frequency is plotted in a color-map**





Summary

- **Ultra-materials ($E_g > 5\ eV$) hold promise for achieving high Figure of Merit (FOM) for power electronics applications**
- **Current materials are still immature in terms of unwanted defects (premature breakdown, low mobility) and challenges in doping (incomplete ionization)**
- **Figure of Merit is one (incomplete) way to relate semiconductor material properties to device performance**
  - Conventional approach to calculating FOM (e.g. Baliga FOM) has been over-simplified, and only address particular applications of power electronics
  - Current work through the co-design thrust of the ULTRA EFRC attempts to correct some of the shortcomings of particular importance for UWBGs
  - New performance metrics in terms of power dissipation in switching power converter applications are currently being developed

Thanks!