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Analysis of the Dependence of Critical Electric Field on Semiconductor Bandgap

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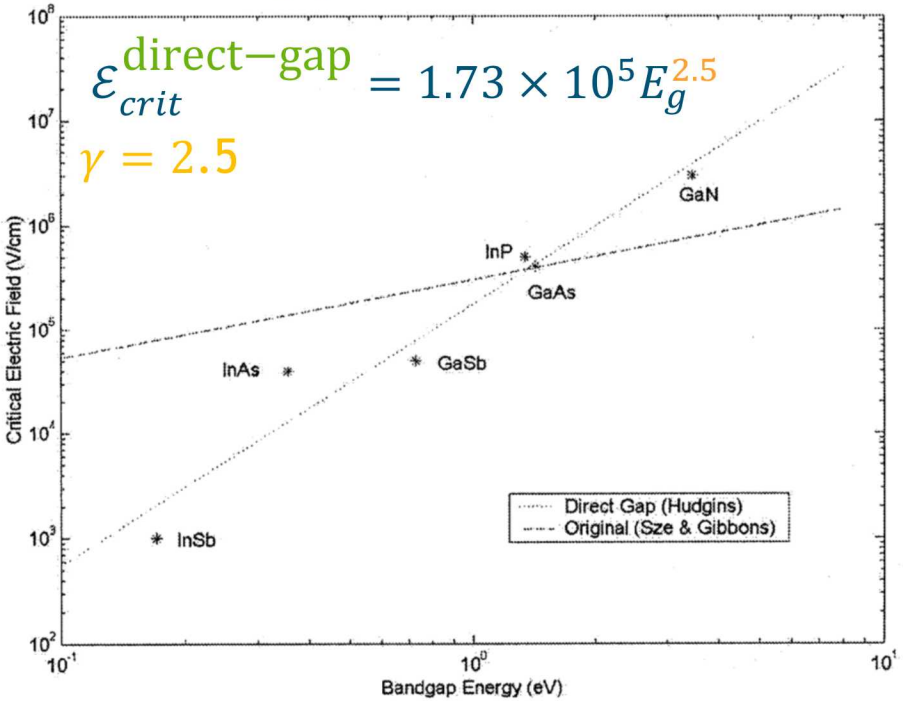
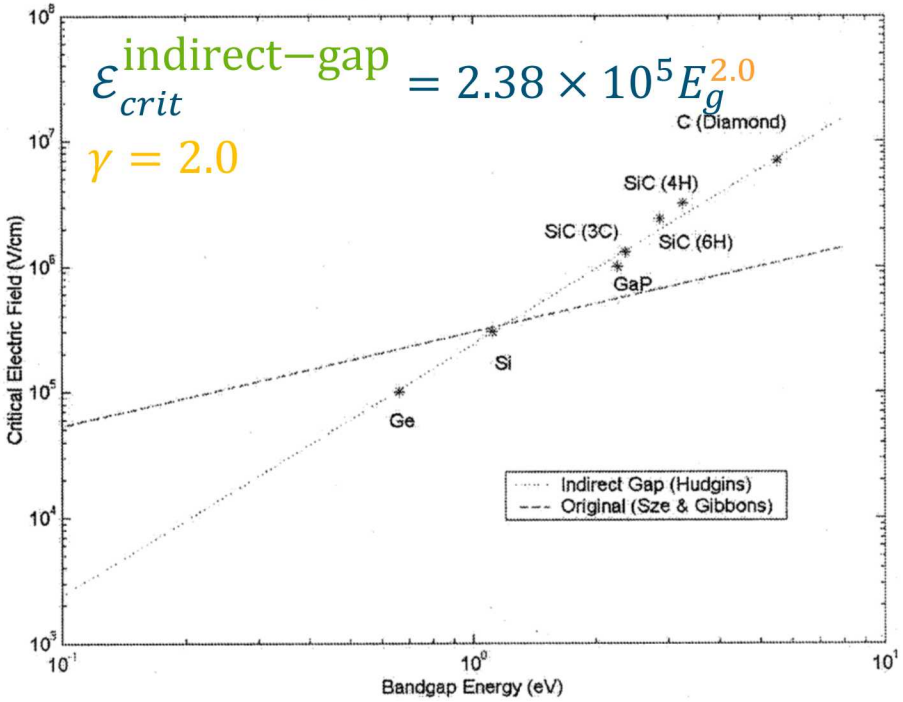
Empirical Fitting of Critical Electric Field on Semiconductor Bandgap

- Empirical fits are used to predict capabilities of emerging power electronics materials: $\mathcal{E}_{crit} \sim E_g^{\gamma}$
- Fits by Hudgins et al. in 2003 remain the standard

Direct Bandgap Material



Indirect Bandgap Material

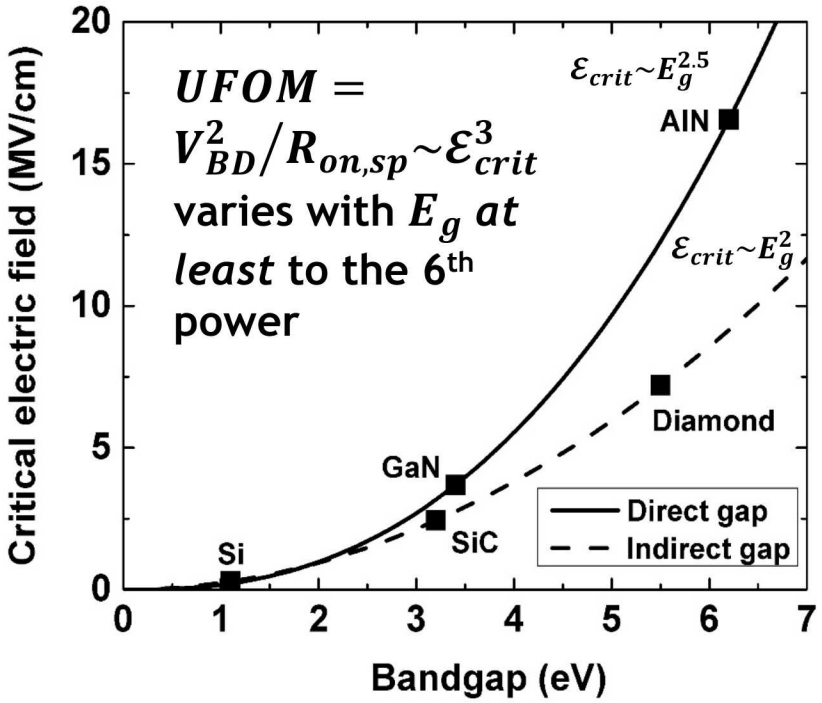


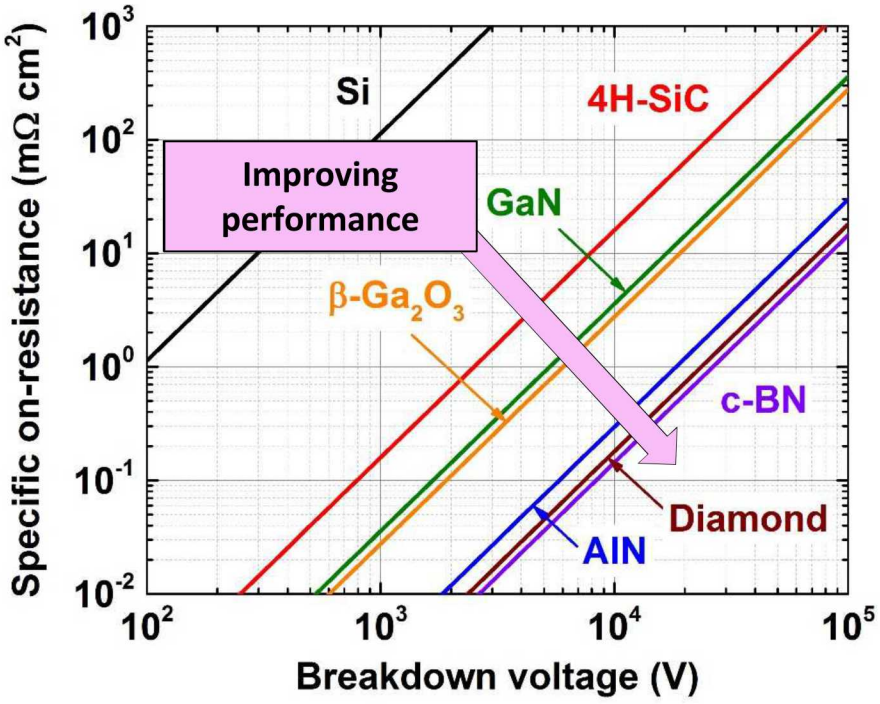
- Empirical fits to data from the literature (not existing theory)
- Not normalized to doping, device structure, temperature
- Subject to device quality

▪ Hudgins et al., *IEEE Trans. on Pow. Elec.*, Vol. 18, No. 3 (2003)

Figures of Merit

Figures of merit often rely on parameters predicted from empirical fits





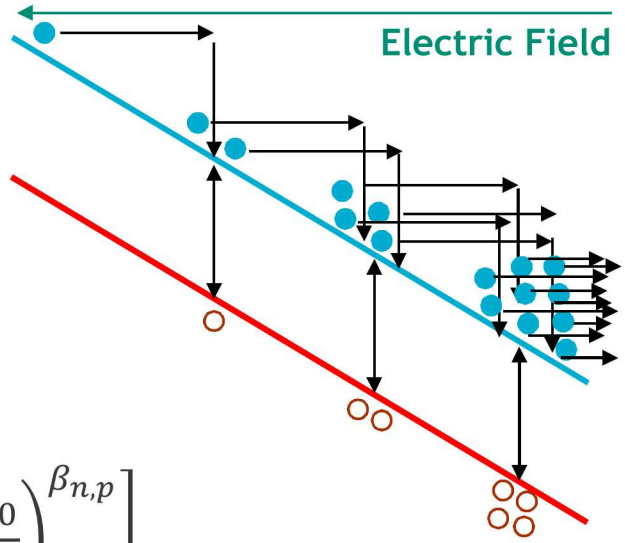
- UFOM only valid for non-punch-through device structures
- UFOM only valid for vertical devices

- Hudgins et al., *IEEE Trans. on Pow. Elec.* **18**, 3 (2003)
- Tsao et al., *Advanced Elec. Mat.* **4**, 1600501 (2018)

Impact Ionization

Impact ionization drives avalanche breakdown in a device

Charge carriers accelerated under high electric fields lose energy and ionizing more electron-hole pairs, resulting in multiplication of charge, leading to rapid increase in current & avalanche breakdown



Carrier ionization rates are given by:

$$\alpha_{n,p} = \alpha_{n0,p0} \cdot exp\left[-\left(\frac{\mathcal{E}_{n0,p0}}{\mathcal{E}}\right)^{\beta_{n,p}}\right]$$

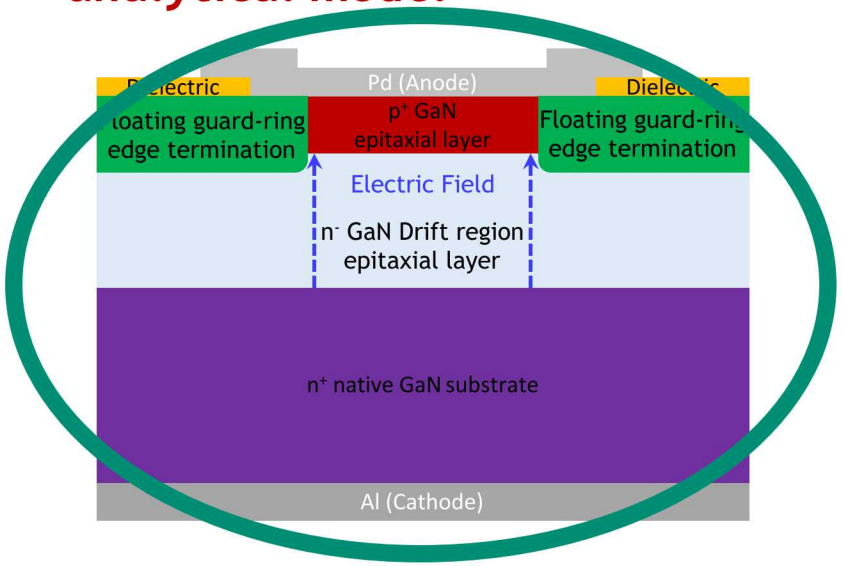
Multiplication factor describes increase in current under impact ionization:

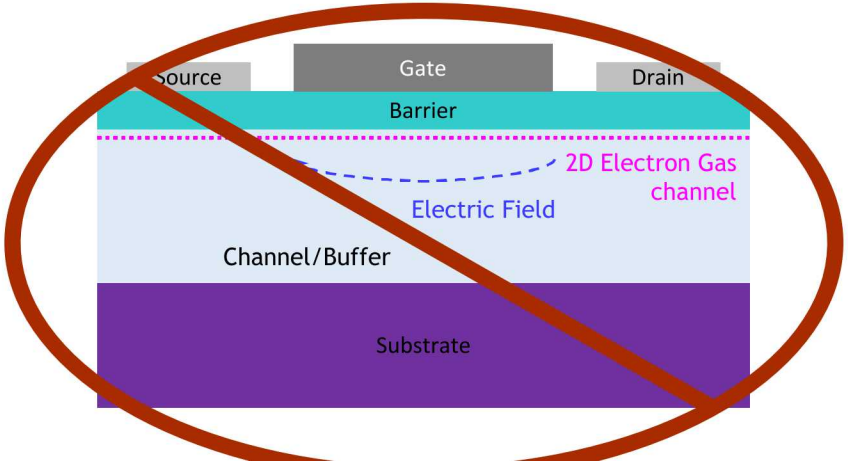
$$M_n = \frac{exp\left[\int_0^{x_D}\left(\alpha_n(x) - \alpha_p(x)\right)dx\right]}{1 - \int_0^{x_D}\alpha_n(x) \cdot exp\left[\int_0^{x}\left(\alpha_p(x') - \alpha_n(x')\right)dx'\right]dx}$$

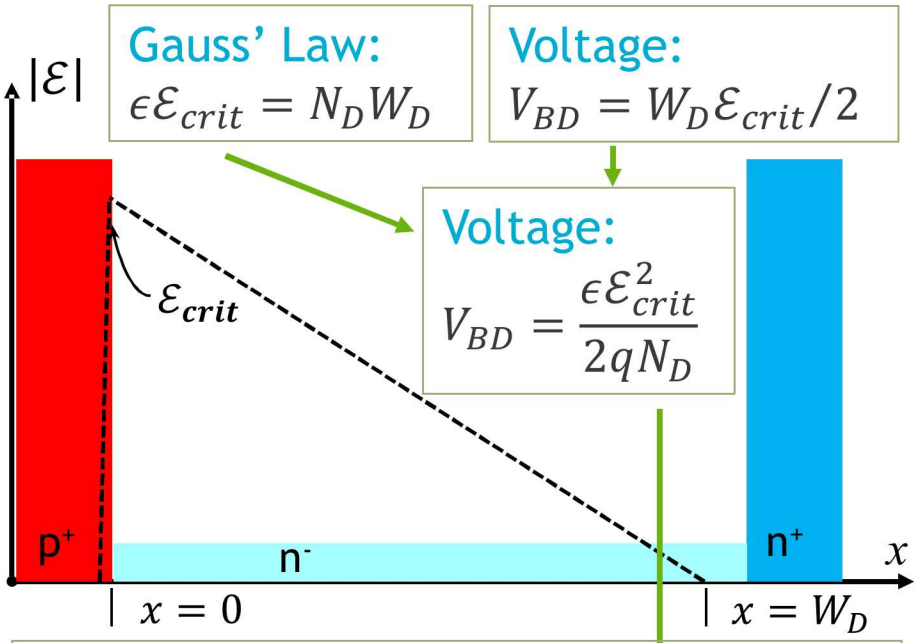
Avalanche occurs when denominator approaches zero

Critical Electric Field and Device Performance

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







Specific on-resistance: $R_{on,sp} = \frac{W_D}{q\mu_n N_D}$

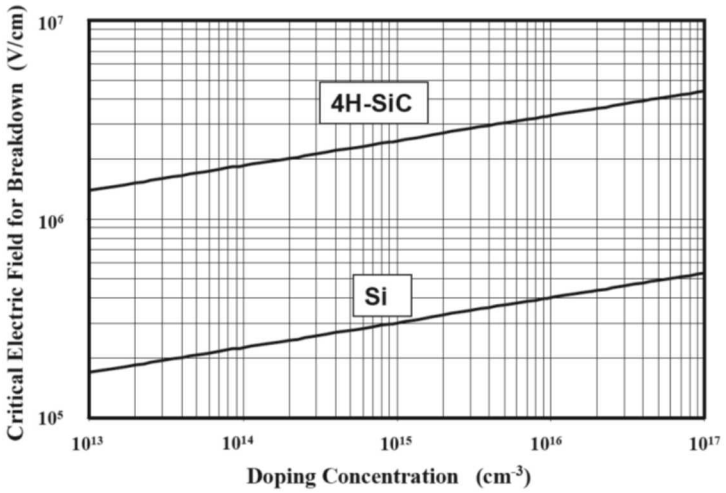
UFOM: $\frac{V_{BD}^2}{R_{on,sp}} = \frac{\epsilon\mu_n\mathcal{E}_{crit}^3}{4}$

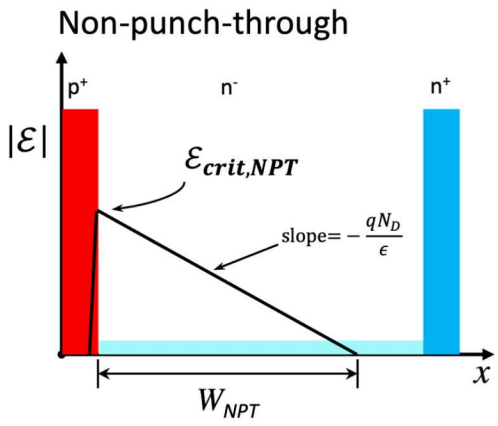
Unipolar Figure of Merit (UFOM)

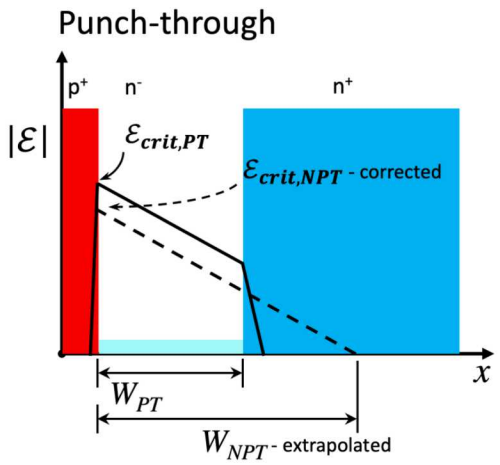
- $\mathcal{E}_{crit}$ is obtained from V_{BD}
- $R_{on,sp}$ is extracted from forward-current slope
- Carrier mobility is often taken from literature

Procedure for Renormalization of $\mathcal{E}_{crit}$ values

- UFOM assumes a given doping and field profile
- Valid comparison of critical electric field between devices requires two major kinds of corrections:
  - Doping:
    - Critical electric field is doping-dependent
    - Devices of different doping levels must be compared to an equivalent doping level
  - Structure
    - Electric fields in non-punch-through (NPT) and punch-through (PT) style devices are not directly comparable
    - To equate, PT devices are transformed into an "equivalent" NPT device (integrated E-field curve is constant)







- B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, 2nd Ed. (2018)

Correction for Doping

Analytical solution for renormalization requires two critical assumptions so the impact ionization integrals in the multiplication factor equation can be evaluated

1. Electron & hole ionization rates are equal: $\alpha_n = \alpha_p$
2. Ionization rate follows a power-law form: $\alpha = \alpha_0 \mathcal{E}^{\delta}$
   - with most-widely accepted : $\delta = 7$

Thus correction for different doping profiles follows:

$$\int_0^{x_{D1}} \alpha(x)dx = \int_0^{x_{D2}} \alpha(x)dx = 1$$

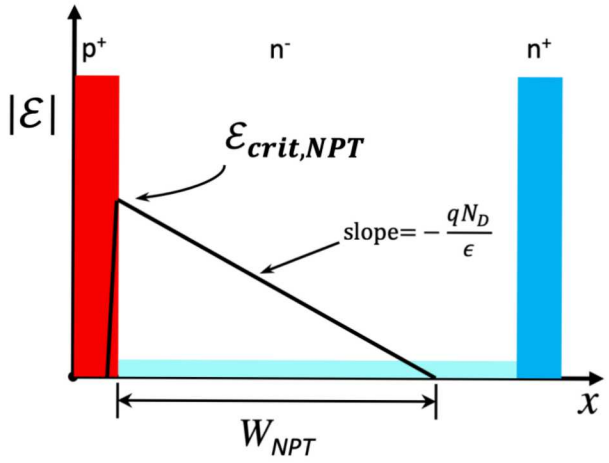
$$\frac{1}{N_{D1}} \int_{\mathcal{E}_{crit1}}^{0} \alpha(\mathcal{E})d\mathcal{E} = \frac{1}{N_{D2}} \int_{\mathcal{E}_{crit2}}^{0} \alpha(\mathcal{E})d\mathcal{E}$$

$$\boxed{\frac{\mathcal{E}_{crit1}}{\mathcal{E}_{crit2}} = \left(\frac{N_{D1}}{N_{D2}}\right)^{1/(\delta+1)}}$$

- B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, 2nd Ed. (2018)

Correction for NPT & PT Device Structure

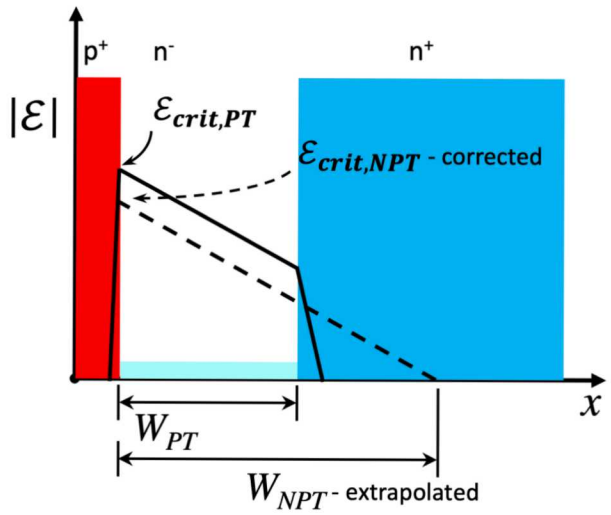
Non-punch-through



$$V_{BD,NPT} = \frac{\epsilon}{2qN_D}\mathcal{E}_{crit,NPT}^2$$

$$\mathcal{E}(x) = \mathcal{E}_{crit,NPT} - \frac{qN_D}{\epsilon}x = \frac{qN_D}{\epsilon}(W_{NPT} - x)$$

Punch-through



$$V_{BD,PT} = \mathcal{E}_{crit,PT}W_{PT} - \frac{qN_D}{2\epsilon}W_{PT}^2$$

$$\mathcal{E}(x) = \mathcal{E}_{crit,PT} - \frac{qN_D}{\epsilon}x | x \le W_{PT}$$

Equating the impact ionization integrals for different electric field profiles:

$$\int_0^{x_{NPT}} \alpha(x)dx = \int_0^{x_{PT}} \alpha(x)dx \quad \Rightarrow \quad \int_{\mathcal{E}_{crit,NPT}}^{0} \alpha(\mathcal{E})d\mathcal{E} = \int_{\mathcal{E}_{crit,PT}}^{\mathcal{E}_{crit,PT}-\frac{qN_D}{\epsilon}W_{PT}} \alpha(\mathcal{E})d\mathcal{E}$$

$$\frac{\mathcal{E}_{crit,NPT}}{\mathcal{E}_{crit,PT}} = \left[1 - \left(1 - \frac{qN_{D,PT}}{\epsilon}\frac{W_{PT}}{\mathcal{E}_{crit,PT}}\right)^{\delta+1}\right]^{1/(\delta+1)}$$

Combined Corrections

Doping and device structure corrections for $\mathcal{E}_{crit}$ combine into:

$$\frac{\mathcal{E}_{crit,NPT}}{\mathcal{E}_{crit,PT}} = \left(\frac{N_{D,NPT}}{N_{D,PT}}\right)^{1/8}\left[1-\left(1-\frac{qN_{D,PT}}{\epsilon}\frac{W_{PT}}{\mathcal{E}_{crit,PT}}\right)^{8}\right]^{1/8}$$

- Using this equation gives us the ability to equate $\mathcal{E}_{crit}$ for devices with different doping and field profiles

Reference:	Drift-Layer Material	N_D (cm^{-3})	W_{PT} (μm)	V_{BD} (V)	$\mathcal{E}_{crit,PT}$ - measured (MV/cm)	$\mathcal{E}_{crit,NPT}$ - corrected (MV/cm)	W_{NPT} - extrapolated (μm)	$\mathcal{E}_{crit,NPT}$ - normalized to $N_D=10^{16}$ cm^{-3} (MV/cm)
Armstrong et al.	GaN	3×10^{15}	30	3930	2.09	2.09	40.10	2.43
Allerman et al.	$Al_{0.3}Ga_{0.7}N$	5×10^{16}	4.3	1627	5.76	5.76	6.26	4.71
Ohta et al.	GaN	9×10^{15}	22	4700	3.86	3.86	24.64	3.91
Hu et al.	GaN	2.5×10^{15}	8	1406	1.93	1.88	25.46	2.23
Nishikawa et al.	GaN	2×10^{16}	0.225	52.375	2.37	1.98	5.68	1.81
Nishikawa et al.	$Al_{0.29}Ga_{0.71}N$	2×10^{16}	0.225	83.75	3.76	3.00	8.16	2.75
Nishikawa et al.	$Al_{0.34}Ga_{0.66}N$	2×10^{16}	0.225	91.125	4.14	3.23	8.72	3.00
Nishikawa et al.	$Al_{0.46}Ga_{0.54}N$	2×10^{16}	0.225	112.5	5.04	3.90	10.26	3.58
Nishikawa et al.	$Al_{0.52}Ga_{0.48}N$	2×10^{16}	0.225	138.75	6.21	4.69	12.20	4.30
Nishikawa et al.	$Al_{0.57}Ga_{0.43}N$	2×10^{16}	0.225	181.5	8.11	5.94	15.30	5.45

- A. M. Armstrong et al., *Elec. Lett.* **52**, 1170 (2016)
- A. A. Allerman et al., *Elec. Lett.* **52**, 1319 (2016)
- H. Ohta et al., *IEEE Elec. Dev. Lett.* **36**, 1180 (2015)
- Z. Hu et al., *App. Phys. Lett.* **107** (2015)
- A. Nishikawa et al., *Jap. Jour. of App. Phys.* **46**, 4B (2007)

Updated $\mathcal{E}_{crit}$ vs. E_g Values

	Semiconductor	Bandgap at 300 K (eV)	Type	Sze	Hudgins	Wang	Our research
Well-established	InSb	0.17	Direct	-	1×10^3	1×10^3	[a]
	InAs	0.354	Direct	-	4×10^4	4×10^4	[a]
	Ge	0.661	Indirect	2.5×10^5	1×10^5	1×10^5	2.0×10^5
	GaSb	0.726	Direct	-	5×10^4	5×10^4	[b]
	$In_{0.53}Ga_{0.47}As$	0.74	Direct	-	-	-	2.84×10^5
	Si	1.12	Indirect	4.37×10^5	3×10^5	3×10^5	3.7×10^5
	InP	1.344	Direct	-	5×10^5	5×10^5	5.0×10^5
	GaAs	1.424	Direct	4.98×10^5	4×10^5	6×10^5	5.4×10^5
	GaP	2.26	Indirect	7.59×10^5	1×10^6	1×10^6	[b]
Widebandgap	3C-SiC	2.36	Indirect	-	1.3×10^6	1×10^6	[c]
	6H-SiC	3.0	Indirect	-	2.4×10^6	5×10^6	2.9×10^6
	4H-SiC	3.23	Indirect	-	3.18×10^6	-	3.2×10^6
	GaN	3.45	Direct	-	3×10^6	5×10^6	3.9×10^6
Ultra-Widebandgap	$Al_xGa_{1-x}N$	3.45-6	Direct	-	-	-	[d]
	β-Ga_2O_3	4.7	Direct	-	-	15×10^6	[d]
	C (diamond)	5.5	Indirect	-	5.7×10^6	21.5×10^6	10.1×10^6

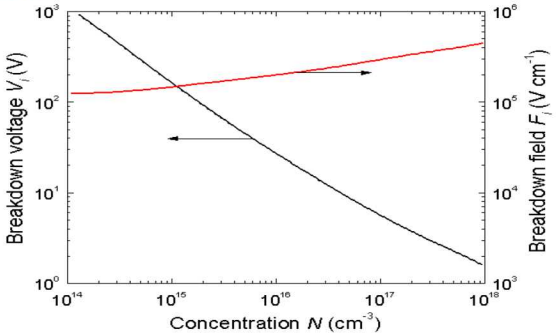
[a] tunneling cannot be decisively excluded as a contributing factor in carrier multiplication
[b] no reliable data in the literature was found
[c] insufficient device data to perform normalization
[d] no experimental data confirming temperature-dependent behavior indicative of true avalanche breakdown

- S. M. Sze and G. Gibbons, *App. Phys. Lett.* 8, 111 (1966)
- Hudgins et al., *IEEE Trans. on Pow. Elec.* **18**, No. 3 (2003)
- L.-M. Wang, 25th *IEEE Int. Conf. on Microelec.* (2006)

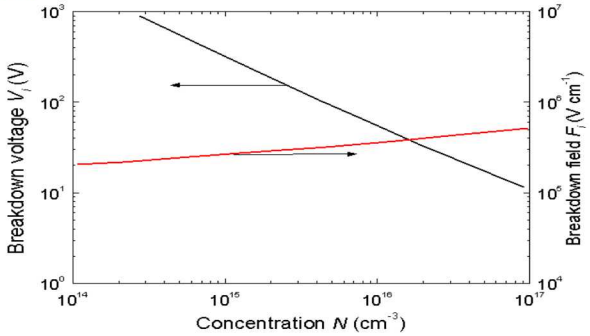
Well-Established Semiconductors

- Impact ionization coefficients and $\mathcal{E}_{crit}$ vs. doping is known for many of the well-established semiconductors
- Compiled in Semiconductor Parameters Volumes 1 & 2 edited by Levinshtein, Rumyantsev & Shur

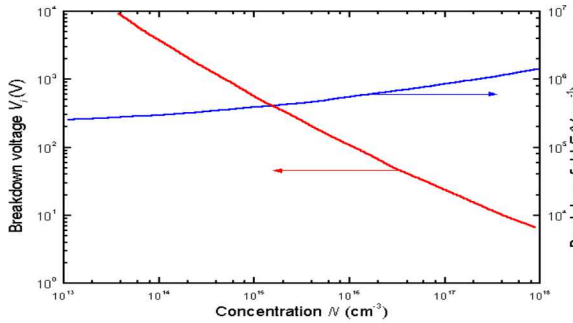
Ge

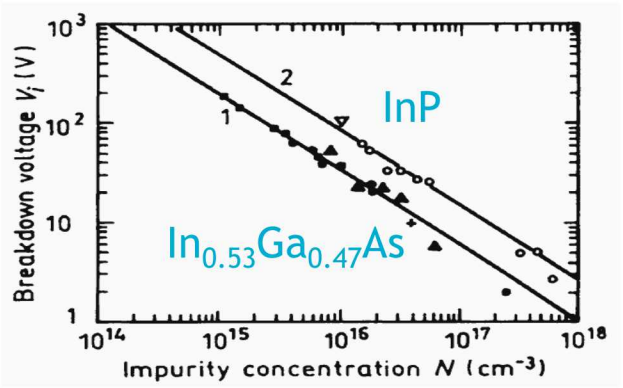


Si

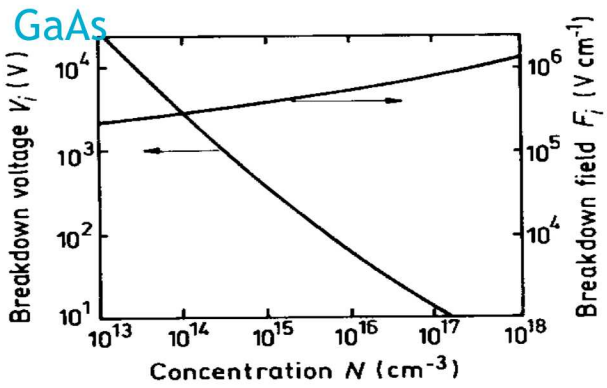


InP





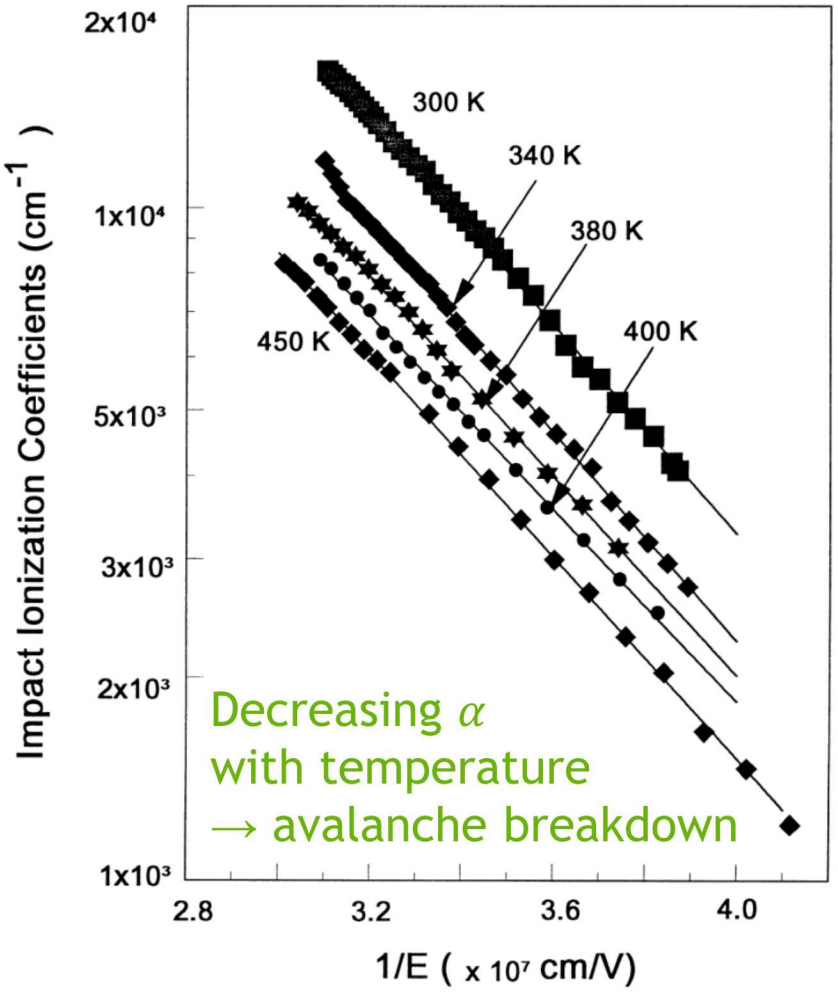
GaAs



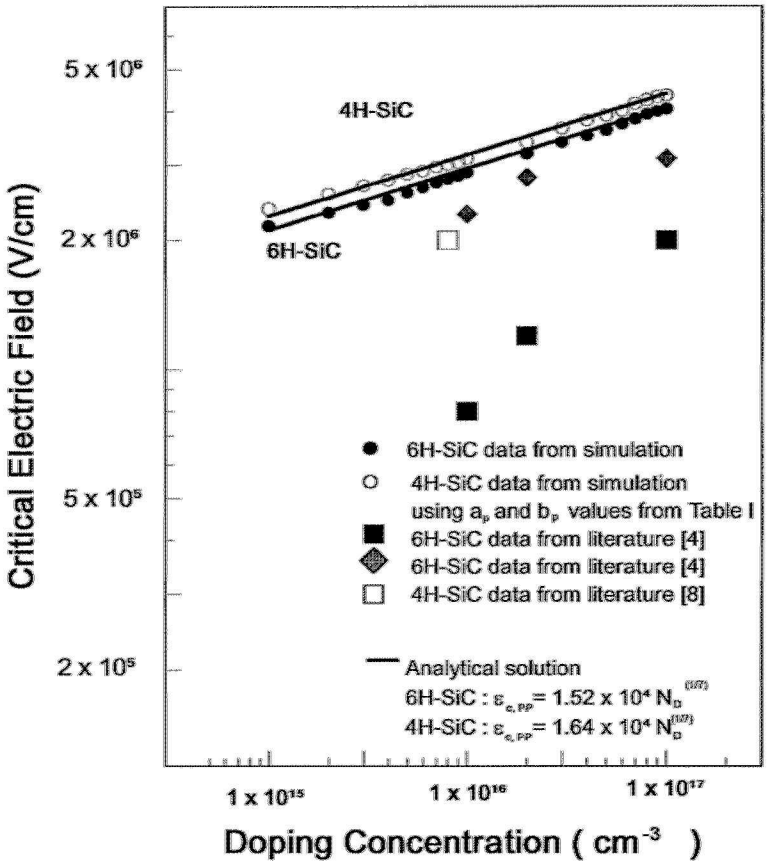
- M. Levinshtein, S. Rumyantsev, M. Shur, *Semiconductor Paramaters Vol. 1* (1996)
- M. Levinshtein, S. Rumyantsev, M. Shur, *Semiconductor Paramaters Vol. 2* (1999)

WBG Semiconductor: SiC

α_p Impact Ionization Data



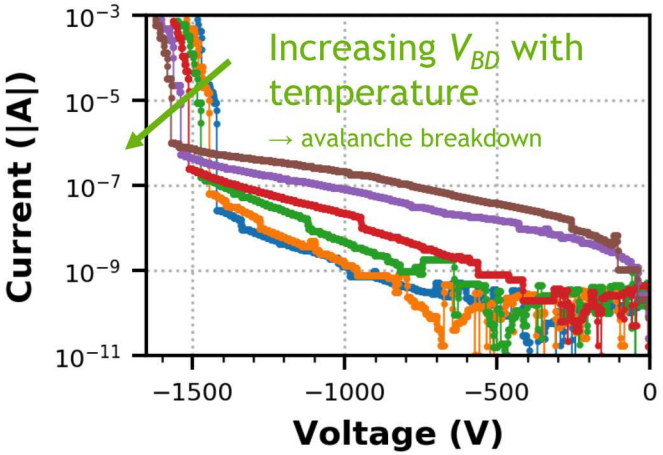
Critical electric field vs. doping

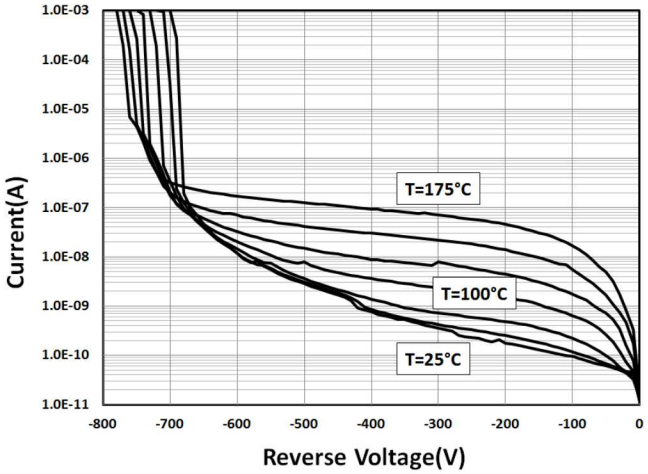


- R. Raghunathan and B.J. Baliga, *Solid-State Elec.* 43 (1999)

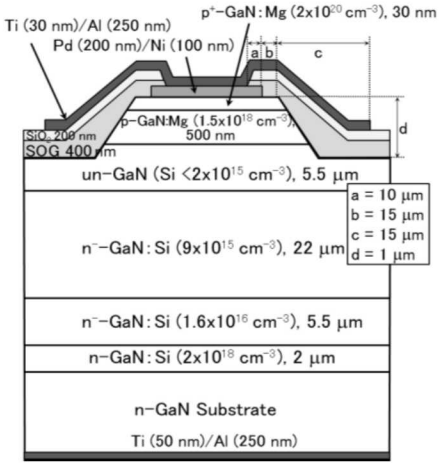
WBG Semiconductor: GaN

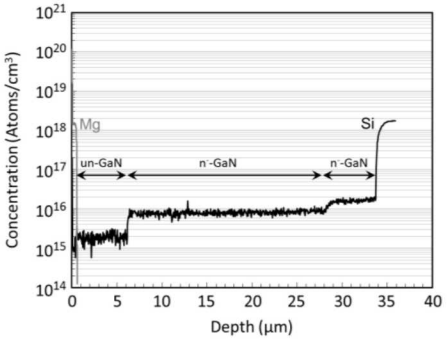
Breakdown vs. Temperature Data

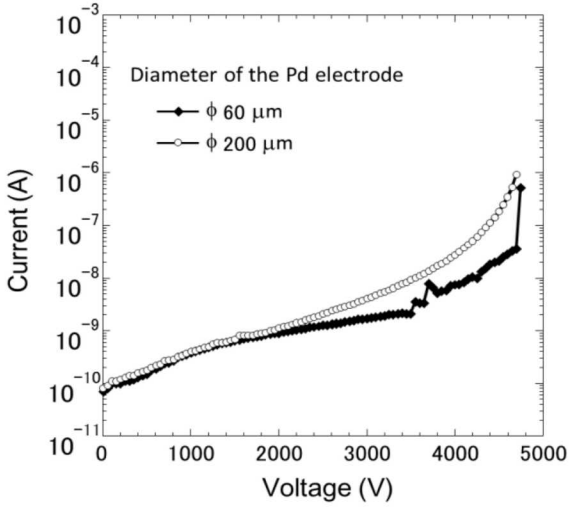




Best Device Reported in Literature



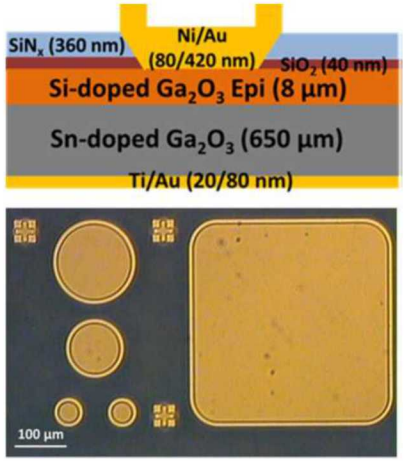


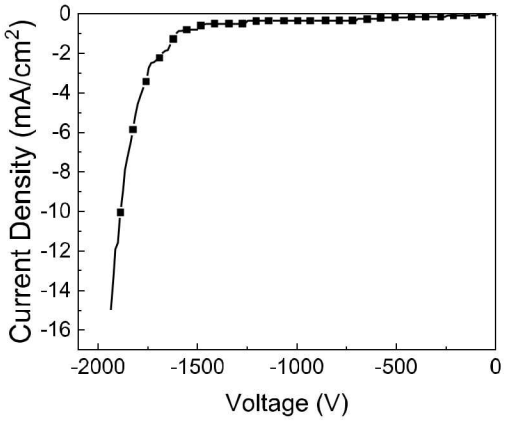


- O. Slobodyan et al., *MRS. Comm.* **8**, 4 (2018)
- I. Kizilyalli et al., *IEEE Trans. On Elec. Dev.* **60**, 10, (2013)
- Ohta et al., *IEEE Elec. Dev. Lett.* **36**, 11, (2015)

UWBG Semiconductors: β-Ga_2O_3 & $Al_xGa_{1-x}N$

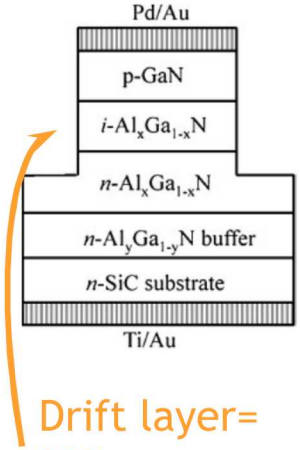
β-Ga_2O_3 has predicted $\mathcal{E}_{crit}$~7 MV/cm



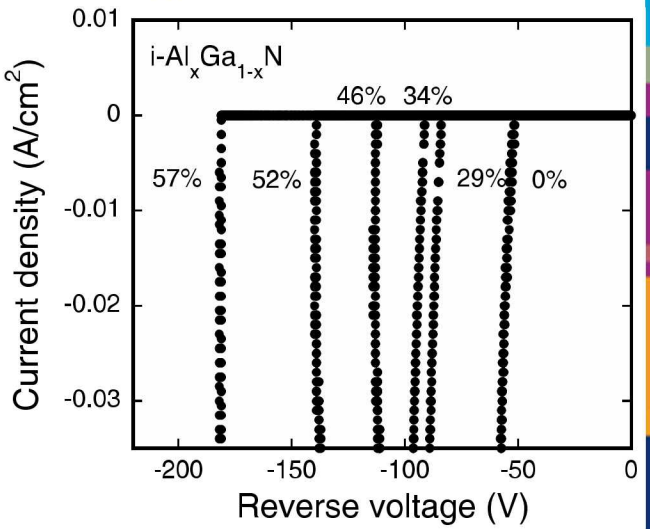


$\mathcal{E}_{crit} = 2.8\ MV/cm$

AlN has predicted $\mathcal{E}_{crit}$~10 MV/cm and GaN $\mathcal{E}_{crit}$~3.9 MV/cm with $Al_xGa_{1-x}N$ alloys values falling in-between



Drift layer= 225 nm



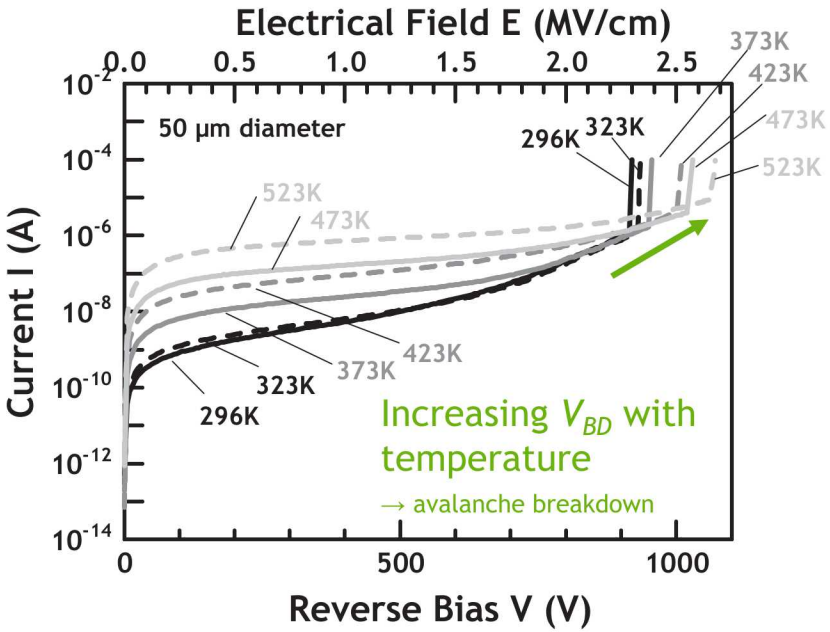
$\mathcal{E}_{crit}^{0\%} = 1.81\ MV/cm$	$\mathcal{E}_{crit}^{29\%} = 2.75\ MV/cm$
$\mathcal{E}_{crit}^{34\%} = 2.96\ MV/cm$	$\mathcal{E}_{crit}^{46\%} = 3.58\ MV/cm$
$\mathcal{E}_{crit}^{52\%} = 4.30\ MV/cm$	$\mathcal{E}_{crit}^{57\%} = 5.45\ MV/cm$

No *current* temperature dependence of breakdown voltage or ionization coefficients support avalanche breakdown in β-Ga_2O_3 or $Al_xGa_{1-x}N$

- J. Yang et al., *ECS Jour. of Sol. State Sci. and Tech.* **8**, 7 (2019)
- A. Nishikawa et al., *Jap. Jour. of App. Phys.* **46**, 4B (2007)

UWBG Semiconductor: C (diamond)

Breakdown vs. Temperature Data



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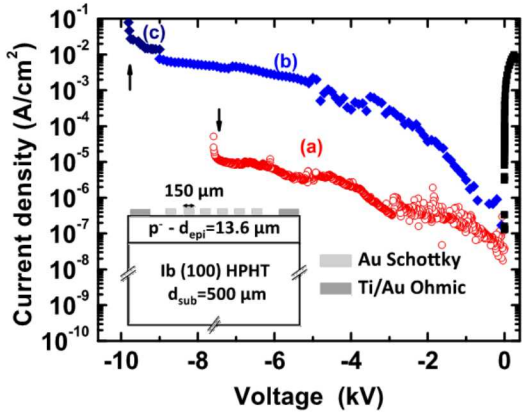
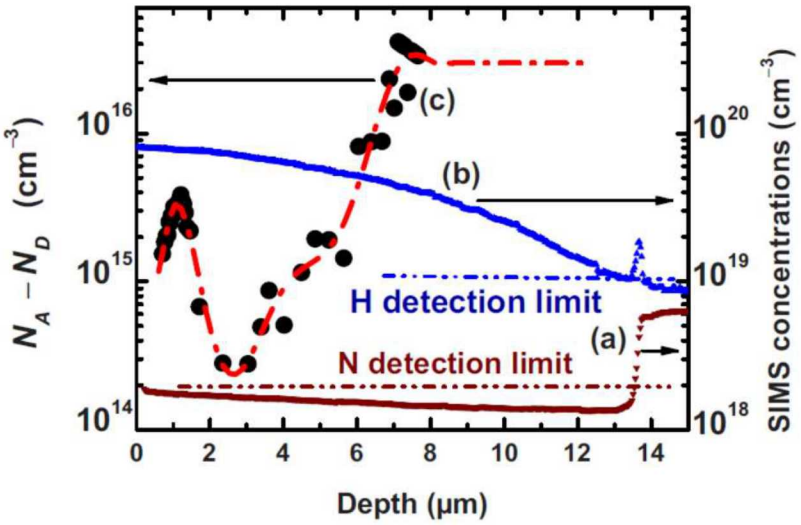


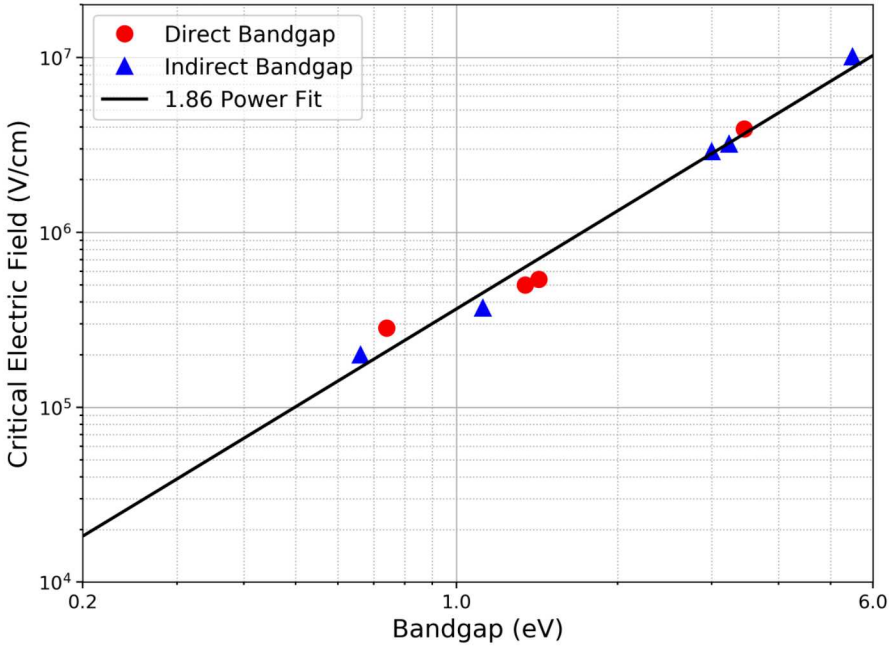
But... a complicated doping profile

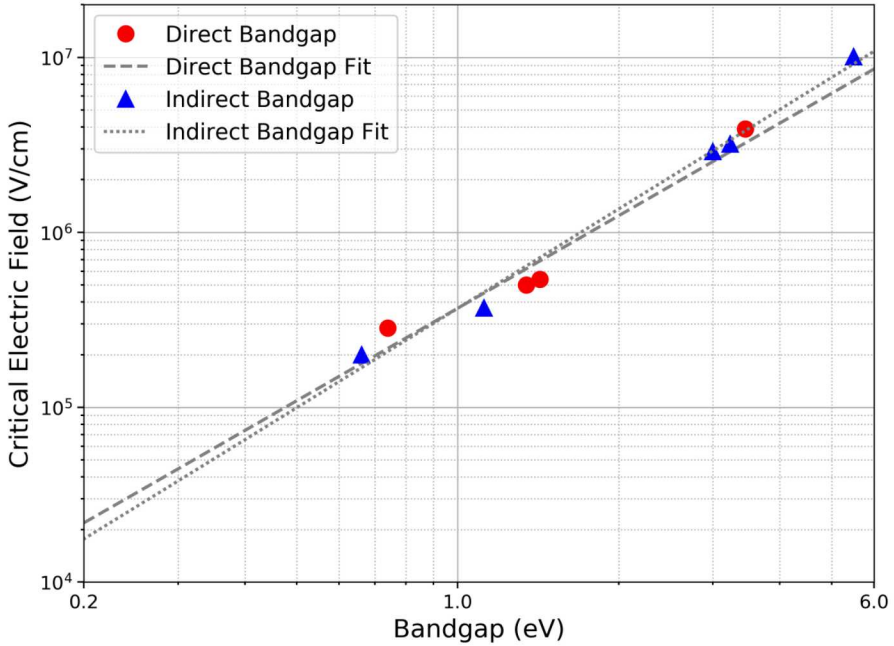


- M. Suzuki et al., *Phys. Stat. Sol. A* **210**, 10 (2013)
- P.-N. Volpe et al., *App. Phyl. Lett.* **97**, (2010)

Fitting of Updated Critical Electric Field vs. Semiconductor Bandgap Values

- Updated power-law fit to new critical electric field values
- Best-fit power-law slope $\mathcal{E}_{crit} \sim E_g^{\gamma}$: $\gamma = 1.86$

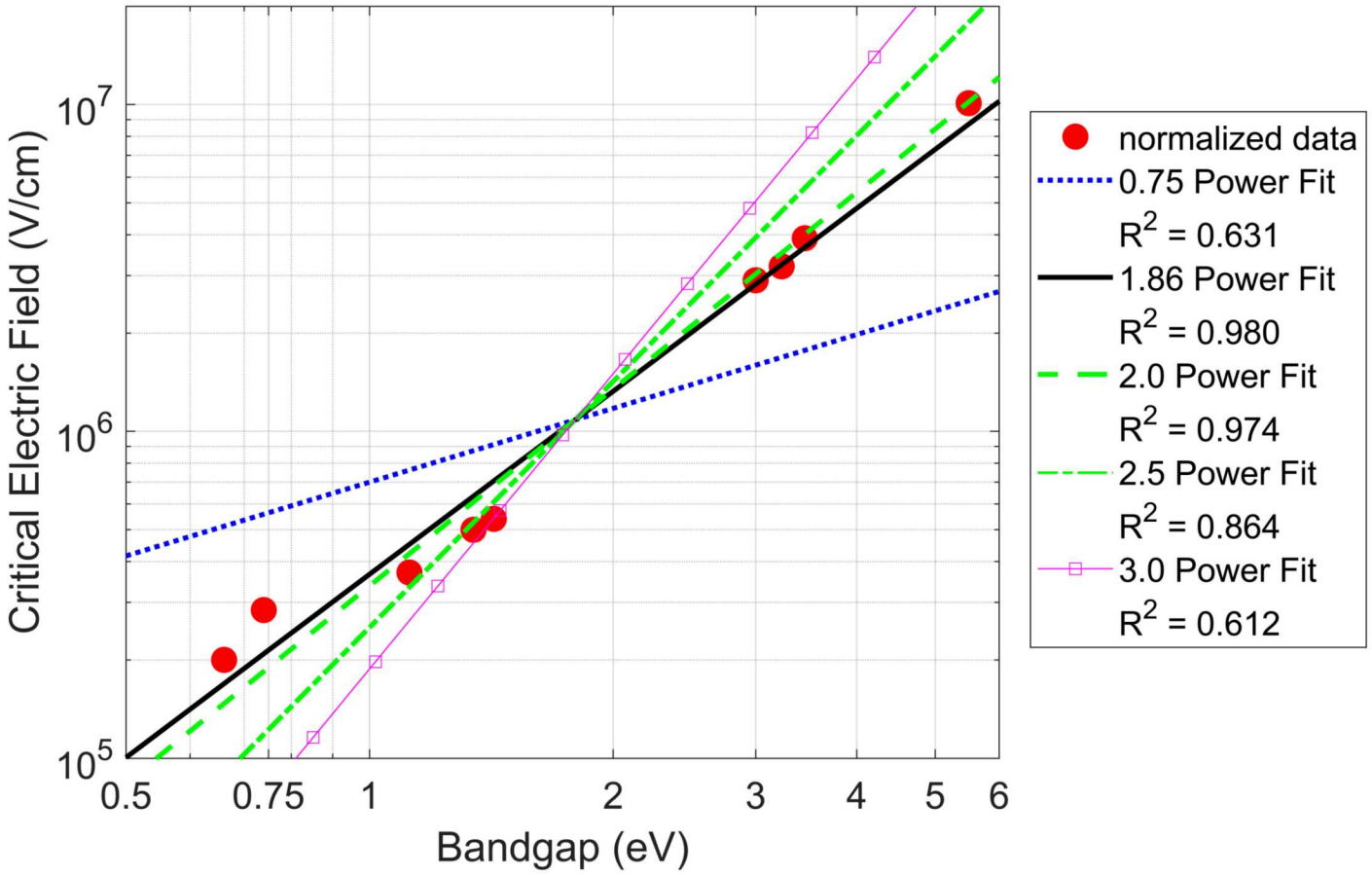




Semiconductor	Type	Bandgap (eV)	Our research
Ge	Indirect	0.661	2.0×10^5
$In_{0.53}Ga_{0.47}As$	Direct	0.74	2.84×10^5
Si	Indirect	1.12	3.7×10^5
InP	Direct	1.344	5.0×10^5
GaAs	Direct	1.424	5.4×10^5
6H-SiC	Indirect	3.0	2.9×10^6
4H-SiC	Indirect	3.23	3.2×10^6
GaN	Direct	3.45	3.9×10^6
C (diamond)	Indirect	5.5	1.01×10^7

Criticial Field Values	Slope	R^2
All	1.86	0.980
Direct Bandgap	1.76	0.947
Indirect Bandgap	1.89	0.992

Comparison of Updated Empirical Fit with Historical Fits



- For normalized data, the proposed 1.86 fit is much better than most historical fits to date
- This fit should more accurately predict material performance capabilities

Simulation: Ridley's Lucky-electron

- To provide fundamental basis for $\mathcal{E}_{crit}$, developed a phenomenological model for breakdown
  - Ionization integral transformed from integral over space → integral over E-field
  - Ionization rate as a function of field is inserted into integral
- Based on the fundamental avalanche model developed by B.K. Ridley ("lucky-drift" model)
  - Higher fidelity in high/low field regimes (compared to Shockley's "lucky electron" or Chenowyth models)
  - More tractable for calculation than Monte Carlo full band approximations

Ridley's Lucky-Drift Model:

$$\alpha\lambda = \frac{1}{x}\left\{e^{-x} + \left(\frac{e^{-2rx^2}}{1-2rx}\right) + P_T\left[e^{-x(1-\zeta)} + \left(\frac{e^{-2rx^2(1-\zeta)} - e^{-x(1-\zeta)}}{1-2rx}\right)\right]\right\}$$

$$x = \frac{E_{th}}{e\mathcal{E}\lambda} \qquad \zeta = \frac{P_T}{2rx^2} \qquad P_T = 1 - e^{-2rx(x-3)}\Big|_{x\geq 3}$$

Lucky-drift can be described by three variables:

- E_{th}, threshold energy required to initiate avalanche
- r, ratio of energy between electron-phonon interaction and electron-electron momentum transfer
- λ, mean free path of electron

Approach is to transform E_{th}, r, and λ into functions dependent on E_g

B.K. Ridley., *Jour. of Phys. C – Sol. State. Phys.* **16**, 3373 (1983)

Determining E_g dependence of Threshold Energy and Phonon Collision loss for Ridley's Lucky Electron Model

E_{th}

- Energy hot carrier must possess to create an electron-hole pair
- Many assume ionization can be initiated by any electron with energy > E_g
- Actual $E \geq 1.5E_g$ as derived by Maes et al.

r

- Average energy loss per phonon collision to the threshold energy

$$r = \frac{\hbar\omega}{[2n(\omega)+1]E_{th}}$$

$\hbar$ is the reduced Planck constant
ω is phonon angular frequency,
$n(\omega)$ is the quantization number.

- Only E_{th} is function of E_g, so r reduces to

$$r \propto {E_g}^{-1}$$

▪ W. Maes, K. de Meyer, R. van Overstraeten, *Sol.-State. Elec.* **33**, 705 (1990)

Determining E_g dependence of Mean-free-path for Ridley's Lucky Electron Model

λ

- Mean free path length of a carrier before thermal relaxation
- Assume nonpolar optical phonon scattering → τ is energy independent and depends inversely on the effective mass (m^*)

For a carrier at E_{th}

$$\lambda = v_g \cdot \tau \qquad \text{with } v_g(E) = \sqrt{\frac{2E}{m^*}} \text{ and } \tau \propto \frac{1}{m^{*\frac{3}{2}}}$$

$$\lambda \propto \frac{1}{m^{*\frac{3}{2}}} \cdot \sqrt{\frac{2E_{th}}{m^*}} \text{ so:} \qquad \lambda \propto \frac{1}{m^{*\frac{3}{2}}} \cdot \frac{E_{th}^{\frac{1}{2}}}{m^{*\frac{1}{2}}} \propto \frac{1}{m^{*\frac{3}{2}}} \cdot \frac{E_g^{\frac{1}{2}}}{m^{*\frac{1}{2}}}$$

A linear relationship between m^* and E_g can also be derived via Bloch Theory for a periodic potential

$$\lambda \propto \frac{1}{E_g^{\frac{3}{2}}} \cdot \frac{E_g^{\frac{1}{2}}}{E_g^{\frac{1}{2}}} \propto \frac{1}{E_g^{\frac{3}{2}}}$$

Use Si values for r, λ to calculate proportionality constants:

$$\lambda_{Si} = 7.1 \text{ nm to } 11.94 \text{ nm}$$

$$r_{Si} = 0.049 \text{ to } 0.063$$

Parameters for Ridley's Lucky Electron Model

Parameter	Value	Reference
Threshold Energy, E_{th}	$1.5 \cdot E_g$	Maes et al.
Ratio of average energy loss per collision to the E_{th} energy, r	$\frac{0.063}{E_g}$	Ridley
Mean relaxation length, λ	$\frac{12 \times 10^{-7}}{{E_g}^{3/2}}$	Several

- B.K. Ridley., *Jour. of Phys. C – Sol. State. Phys.* **16**, 3373 (1983)
- W. Maes, K. de Meyer, R. van Overstraeten, *Sol.-State. Elec.* **33**, 705 (1990)
- W. Maes, K. de Meyer, R. van Overstraeten, *Sol.-State. Elec.* **33**, 705 (1990)
- T. H. Ning, C. M. Osburn, and H. N. Yu, *Jour. of App. Phys.* **48**, 286 (1977)
- T. Simon, K. Ping-Keung, and H. Chenming, *IEEE Trans. on Elec. Dev.* **31**, 1116 (1984)
- J. W. Slotboom et al., *1987 Inter. Elec. Dev. Meeting* (1987)
- Y. Z. Chen and T. W. Tang, *Jour. of App. Phys.* **65**, 4279 (1989)
- F. M. Abou El-Ela and I. M. Hamada, *Fizika A* **13**, 89 (2004)

Flow Diagram for Simulation of Ridley's Lucky Electron Model

Materials constants
Dielectric constant: ϵ
Bandgap: E_g

Device Parameters
Doping: N_D

Calculate
Threshold energy: E_{th}
Mean free path: λ
Energy loss ratio: r

Applied Voltage: V

Calculate Maximum Electric Field: $\vec{\mathcal{E}}_{max} = \sqrt{\frac{2\epsilon_s \epsilon_0 V}{qN_D}}$

Calculate "Lucky Drift" Ionization rates: α_n & α_p

Calculate Electron & hole multiplication coefficients M_n & M_p:

$$M_n = \frac{\epsilon_r \epsilon_0}{qN_D} \int_{\mathcal{E}_{max}}^{0} \alpha_p(\mathcal{E}) \cdot exp\left[\frac{\epsilon_r \epsilon_0}{qN_D} \int_{\mathcal{E}_{max}}^{\mathcal{E}} \left(\alpha_n(\mathcal{E}') - \alpha_p(\mathcal{E}')\right) d\mathcal{E}'\right] d\mathcal{E} \longrightarrow 1$$

$$M_p = \frac{\epsilon_r \epsilon_0}{qN_D} \int_{\mathcal{E}_{max}}^{0} \alpha_n(\mathcal{E}) \cdot exp\left[\frac{\epsilon_r \epsilon_0}{qN_D} \int_{\mathcal{E}}^{0} \left(\alpha_p(\mathcal{E}') - \alpha_n(\mathcal{E}')\right) d\mathcal{E}'\right] d\mathcal{E} \longrightarrow 1$$

Are either >1?

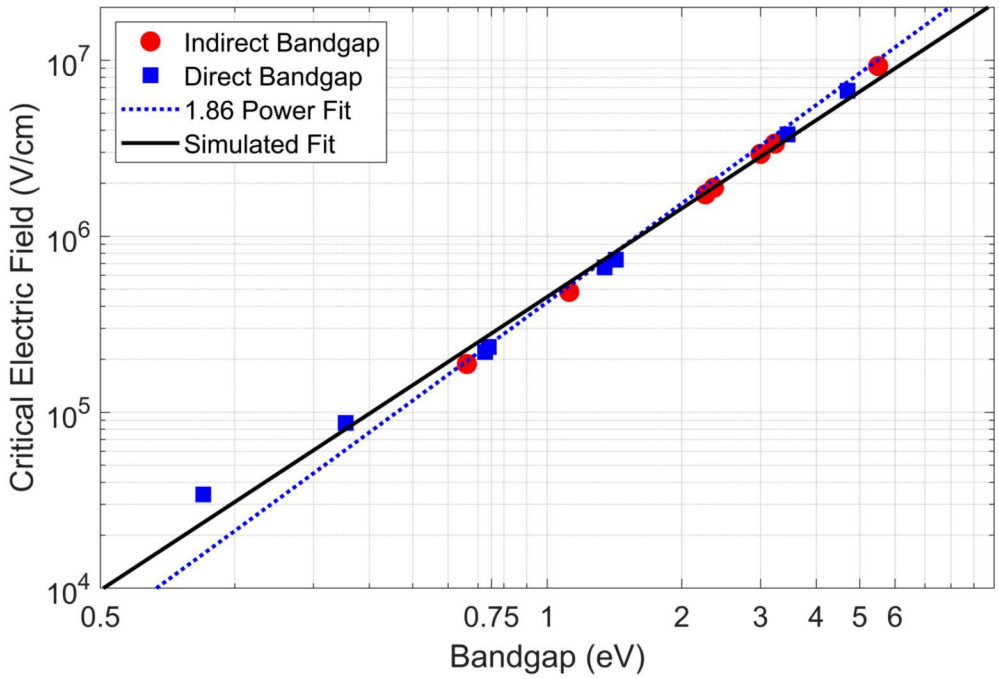
YES → $\mathcal{E}_{crit} = \mathcal{E}_{max}$

Avalanche Breakdown

NO → Iterate voltage: $V_{i+1} = V_i + \Delta V$

Comparison of Empirical Fit and Simulation Results

- Empirical and simulated values are in reasonable agreement



Semiconductor	Bandgap (eV)	Our research	Simulated
InSb	0.17	-	3.41×10^4
InAs	0.354	-	8.70×10^4
Ge	0.661	2.0×10^5	1.88×10^5
GaSb	0.726	-	2.20×10^5
$In_{0.53}Ga_{0.47}As$	0.74	2.84×10^5	2.35×10^5
Si	1.12	3.7×10^5	4.83×10^5
InP	1.344	5.0×10^5	6.65×10^5
GaAs	1.424	5.4×10^5	7.36×10^5
GaP	2.26	-	1.73×10^6
3C-SiC	2.36	-	1.89×10^6
6H-SiC	3.0	2.9×10^6	2.94×10^6
4H-SiC	3.23	3.2×10^6	3.36×10^6
GaN	3.45	3.9×10^6	3.80×10^6
β-Ga_2O_3	4.7	-	6.71×10^6
C (diamond)	5.5	1.01×10^7	9.27×10^6

Criticial Field Values	Slope	R^2
Empirical	1.86	0.980
Simulation	1.67	0.990

Conclusions & Precations

- Updated critical electric field vs semiconductor bandgap values
  - Performed re-normalization to properly compare devices with different dopings and structures
  - Power-law slope of: 1.86 is best fit
    - No difference between direct against indirect bandgap semiconductors
- Performed first-principles physics simulation to determine $\mathcal{E}_{crit}$ for various semiconductors
  - Reasonable agreement with empirical data

- Future development of WBG & UWBG materials is expected to change some critical field values
- Not valid for high-electron mobility transistors (HEMTs) or lateral devices!
  - Electric field profiles are very different