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Dependence of Critical Electric Field on Semiconductor Bandgap—An Analytical Study

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Part 1

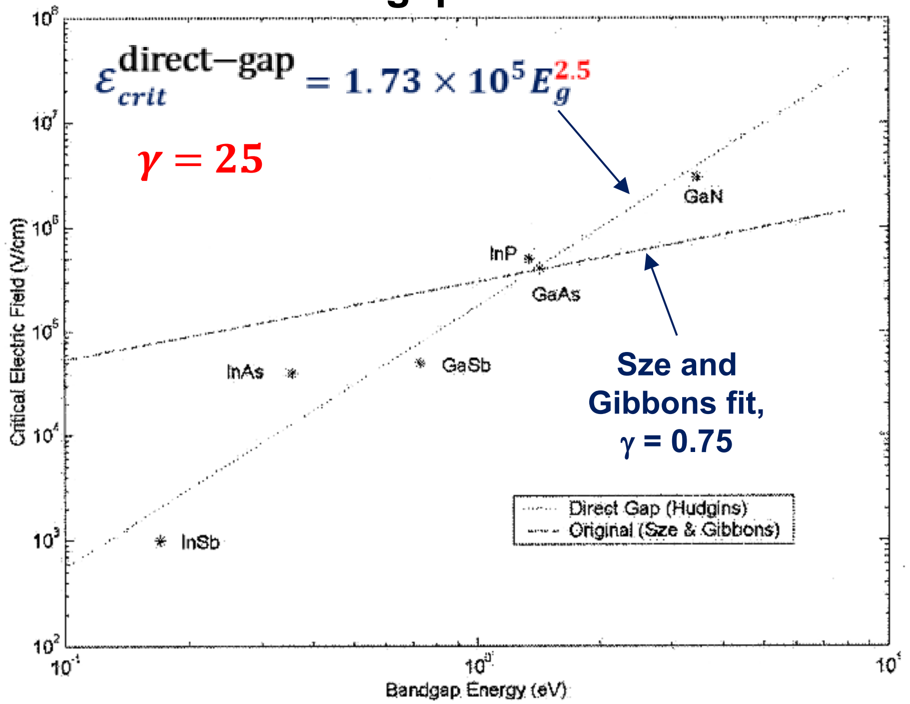
Motivation for Part 1

- Clear up discrepancies in the literature on the critical field E_{crit} for wide- and ultrawide-bandgap materials of interest
- Determine the best power-law fit to $E_{crit} \sim E_g^{\gamma}$, where γ has been under question for some time
  – Use best available measured data across a wide range of non-WBG and WBG/UWBG semiconductors
- Develop an avalanche-breakdown theory to explain the observed power law

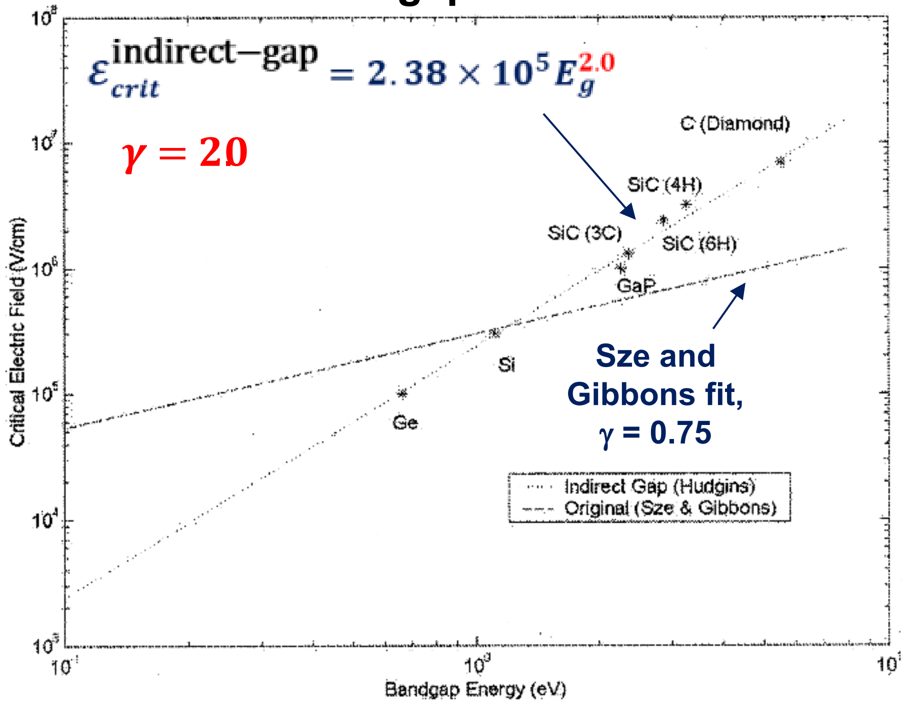
Part 1: Dependence of Critical Electric Field on Semiconductor Bandgap

- Empirical fits are used to predict capabilities of emerging materials and devices: $E_{crit} \sim E_g^{\gamma}$
- Fits by Hudgins et al. published in 2003 have been the only "standard"

Direct-Bandgap Semiconductors



Indirect-Bandgap Semiconductors

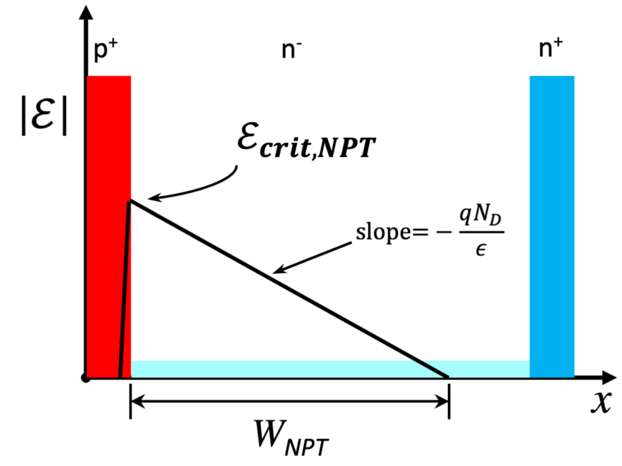


- Empirical fits to data from the literature (some questionable; no existing theory)
- Not normalized to doping, device structure, or temperature
- Subject to material and device quality

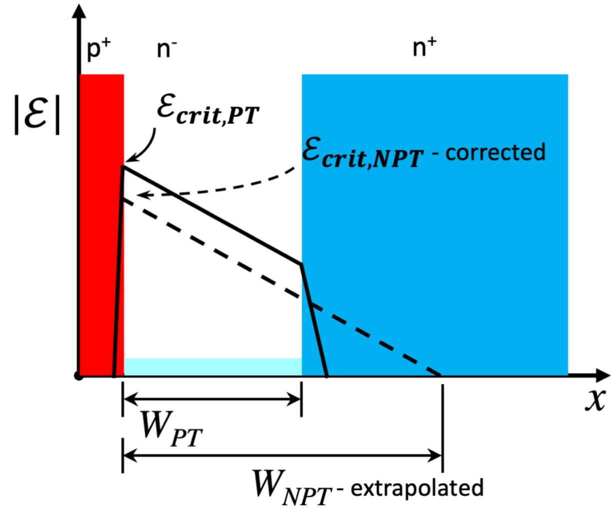
- S. M. Sze and G. Gibbons, *Appl. Phys. Lett.* 8, 111 (1966)
- Hudgins *et al.*, *IEEE Trans. Power Elec.* 18(3), 907 (2003)

Normalizing Literature E_{crit} Data to a Level Playing Field *

Non-Punch-Through Diode



Punch-Through Diode



- **Valid comparison of measured E_{crit} values in different devices / materials requires normalization of doping and structure (punch-through to non-punch-through)**

→ **Transformation equation:**

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

* Slobodyan, *et al.*, in preparation

Normalized Literature Cases *

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

- **This equation gives us the ability to normalize and compare E_{crit} values measured in diodes made of different materials and 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=1x10^{16} cm^{-3} (MV/cm)
Armstrong et al.	GaN	3x10^{15}	30	3930	2.2	2.2	37.9	2.5
Allerman et al.	$Al_{0.3}Ga_{0.7}N$	5x10^{16}	4.3	1627	5.9	5.9	6.0	4.8
Ohta et al.	GaN	9x10^{15}	22	4700	3.1	3.1	31.3	3.4
Hu et al.	GaN	2.5x10^{15}	8	1406	1.9	1.8	53.0	2.3
Nishikawa et al.	GaN	2x10^{16}	0.225	52	2.4	2.0	5.25	1.8
Nishikawa et al.	$Al_{0.29}Ga_{0.71}N$	2x10^{16}	0.225	84	3.8	3.0	7.7	2.8
Nishikawa et al.	$Al_{0.34}Ga_{0.66}N$	2x10^{16}	0.225	91	4.1	3.3	8.25	3.0
Nishikawa et al.	$Al_{0.46}Ga_{0.54}N$	2x10^{16}	0.225	113	5.1	3.9	9.81	3.6
Nishikawa et al.	$Al_{0.52}Ga_{0.48}N$	2x10^{16}	0.225	139	6.2	4.7	11.7	4.3
Nishikawa et al.	$Al_{0.57}Ga_{0.43}N$	2x10^{16}	0.225	182	8.1	6.0	14.7	5.5
Volpe et al.	C (diamond)	1.6x10^{16}	13.6	9800	11.0	11.0	19.8	10
Yang et al.	β-Ga_2O_3	6.1x10^{15}	8	1900	2.8	2.8	25.3	3.0

Corrections can be significant

*** Slobodyan, *et al.*, in preparation**

- 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(11)**, 1180 (2015)
- Z. Hu *et al.*, *App. Phys. Lett.* **107**, 243501 (2015)
- A. Nishikawa *et al.*, *Jap. J. Appl. Phys.* **46(4B)**, 2316 (2007)
- Volpe *et al.*, *App. Phys. Lett.* **97**, 223501 (2010); Yang *et al.*, *ECS JSSST* **8**, Q3028 (2019)

Derived E_{crit} Values for Different Materials *

	Semiconductor	Bandgap at 300 K (eV)	Type	Critical-Field Values (V/cm): Sze	Hudgins	Wang	Our analysis
Conventional	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	-	-	-	2.8×10^5
	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
Wide-Bandgap	GaP	2.26	Indirect	7.59×10^5	1×10^6	1×10^6	[b]
	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
Ultrawide-Bandgap	4H-SiC	3.23	Indirect	-	3.2×10^6	-	3.2×10^6
	GaN	3.45	Direct	-	3×10^6	5×10^6	3.4×10^6
	$Al_xGa_{1-x}N$	3.45-6	Direct	-	-	-	[d]
	β-Ga_2O_3	4.7	Direct	-	-	1.5×10^7	[d]
	C (diamond)	5.5	Indirect	-	5.7×10^6	2.2×10^7	1.0×10^7

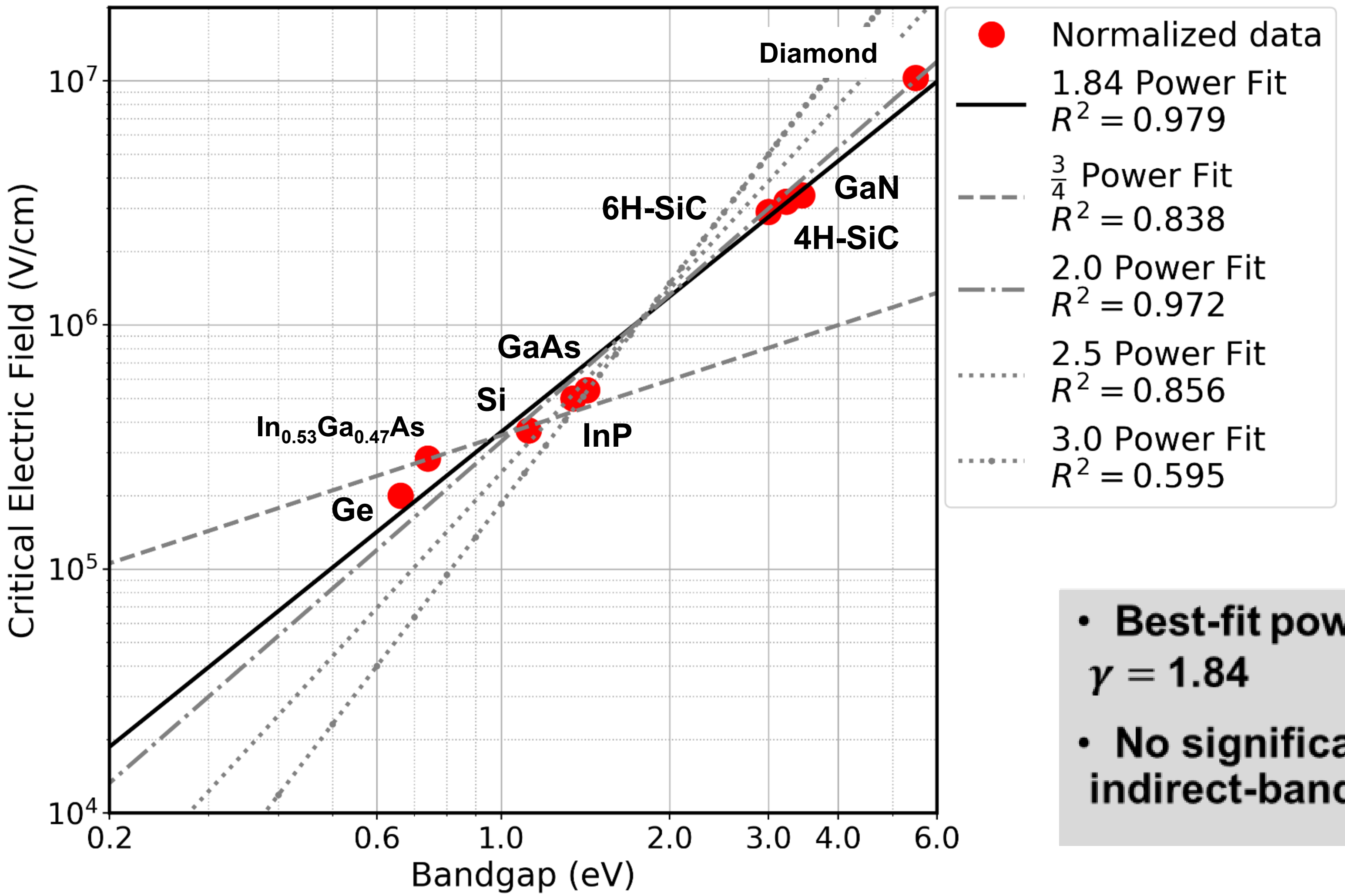
[a] Tunneling cannot be decisively excluded as a contributing factor in breakdown
[b] No reliable data in the literature was found (e.g. material quality is suspect)
[c] Insufficient device data to perform normalization
[d] No experimental data confirming temperature-dependent behavior indicative of avalanche breakdown

- **Correct normalization provides the most reliable values**

- S. M. Sze and G. Gibbons, *Appl. Phys. Lett.* **8**, 111 (1966)
- Hudgins *et al.*, *IEEE Trans. Power Elec.* **18(3)**, 907 (2003)
- L.-M. Wang, *25th IEEE Int. Conf. on Microelec.* (2006)

*** Slobodyan, *et al.*, in preparation**

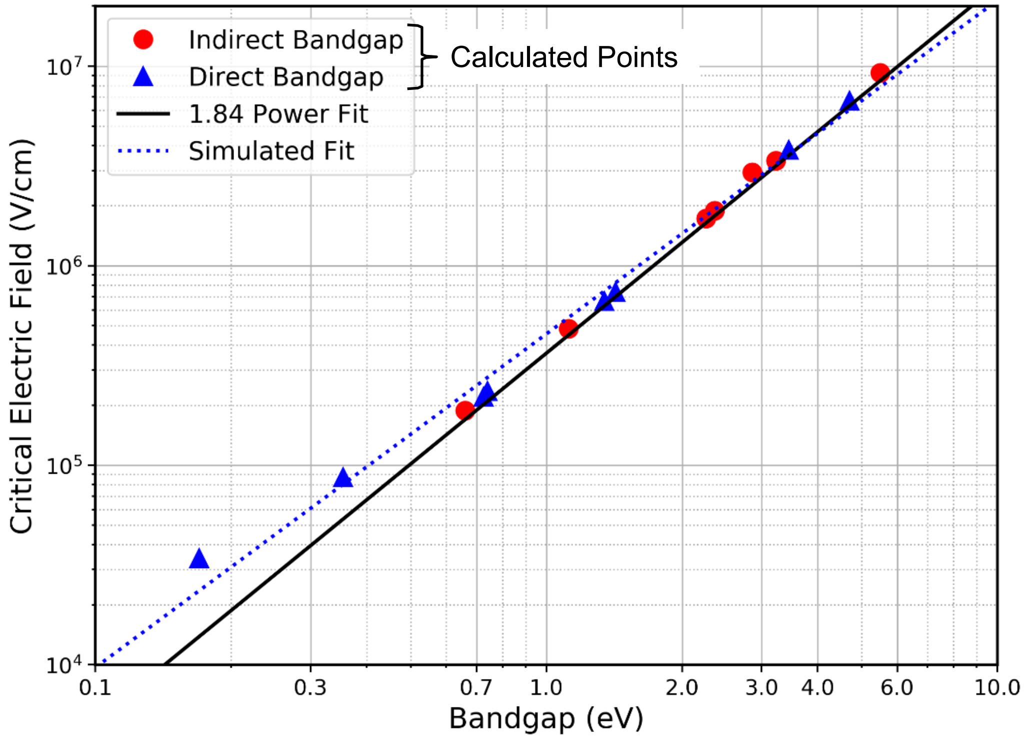
Correct Normalization Gives New Power Law *



- **Best-fit power-law slope gives $E_{crit} \sim E_g^{\gamma}$ with $\gamma = 1.84$**
- **No significant difference between direct- and indirect-bandgap materials**

*** Slobodyan, *et al.*, in preparation**

Developed an Avalanche-Breakdown Model *



Semiconductor	Bandgap (eV)	Corrected data	Simulated (V/cm)
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	2.8×10^5	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	3.4×10^6	3.80×10^6
β-Ga_2O_3	4.7	-	6.71×10^6
C (diamond)	5.5	1.0×10^7	9.27×10^6

Critical Field Values	Slope	R^2
Empirical	1.84	0.979
Simulation	1.67	0.990

*** Slobodyan, *et al.*, in preparation**

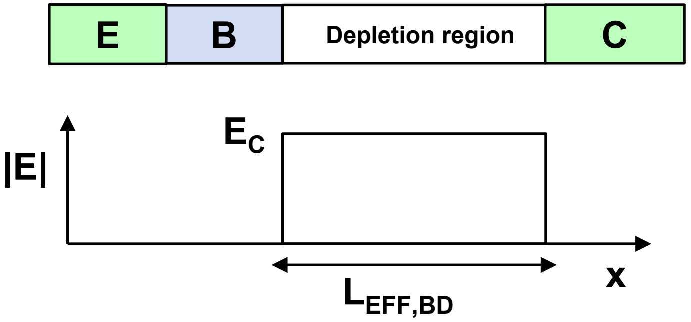
- **Built an avalanche-breakdown model based on Ridley's 'lucky-drift' theory [1]**
- **Power-law fits to normalized data and simulated values of E_{crit} are in good agreement**

1. **B. Ridley, *J. Phys. C--Solid State Phys.* 16, 3373, 1983**

Part 2

Different Cases for "Johnson" FOM

Johnson FOM:
(actually done for BJTs)



- Uniform, rectangular field profile

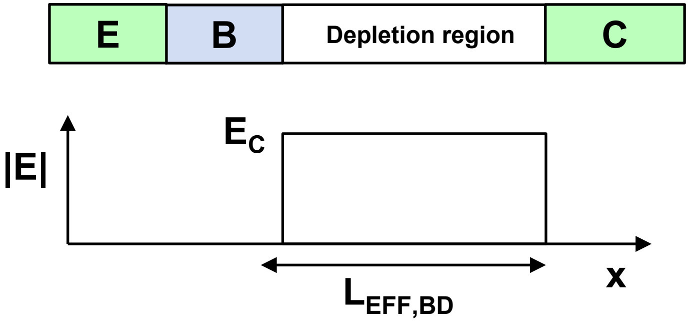
→ $V_{MAX} = E_C L_{EFF}$

→ Johnson FOM (for BJTs): $V_{MAX} f_T = \frac{v_{SAT} E_c}{2\pi}$

$L_{EFF,BD}$ = effective gate length at V_{BKDN}

Different Cases for "Johnson" FOM

Johnson FOM:
(actually done for BJTs)



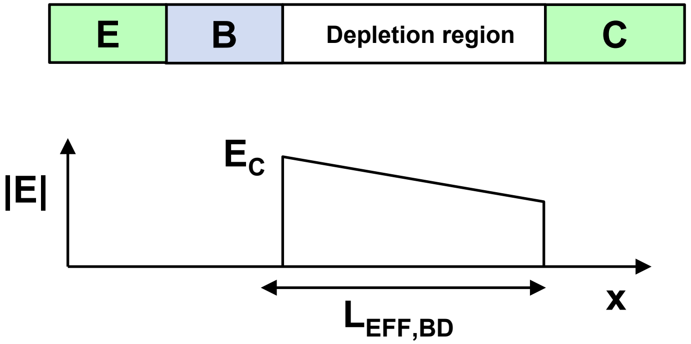
- Uniform, rectangular field profile (low or undoped collector)

→ $V_{MAX} = E_C L_{EFF}$

→ Johnson FOM (for undoped-collector BJTs):

$$V_{MAX} f_T = \frac{v_{SAT} E_c}{2\pi}$$

Quasi-Johnson FOM:



- Field profile for doped collector

→ $V_{MAX} < E_C L_{EFF}$

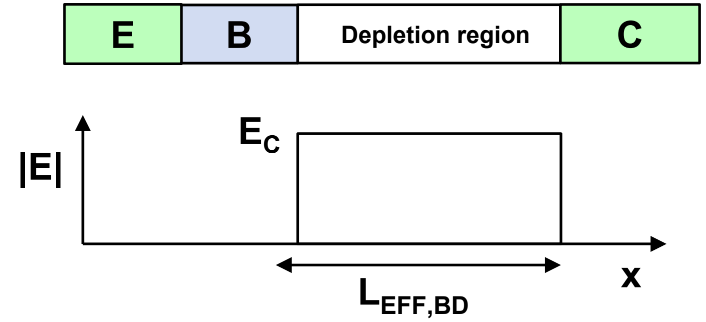
→ Johnson FOM (for doped-collector BJTs):

$$V_{MAX} f_T < \frac{v_{SAT} E_c}{2\pi}$$

$L_{EFF,BD}$ = effective gate length at V_{BKDN}

Different Cases for "Johnson" FOM

Johnson FOM:
(actually done for BJTs)

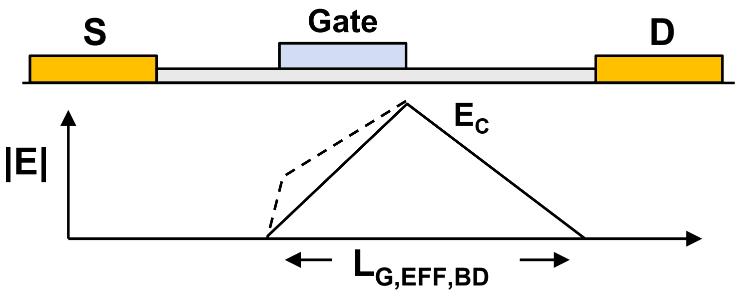


- Uniform, rectangular field profile

→ $V_{MAX} = E_C L_{EFF}$

→ Johnson FOM (for BJTs): $V_{MAX} f_T = \frac{v_{SAT} E_c}{2\pi}$

First-order Johnson/Hollis:



- Triangular field profile, for non-gate-overlapping FETs

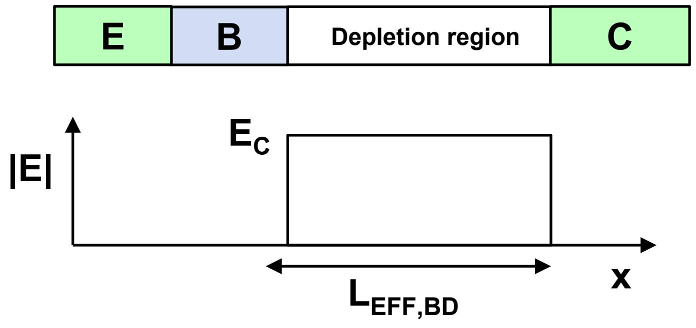
→ $V_{MAX} \approx E_C L_{EFF} / 2$

→ Johnson/Hollis FOM for FETs: $V_{MAX} f_T = \frac{v_{SAT} E_c}{4\pi}$

$L_{G,EFF,BD}$ = effective gate length at V_{BKDN}

Different Cases for "Johnson" FOM

Johnson FOM:
(actually done for BJTs)

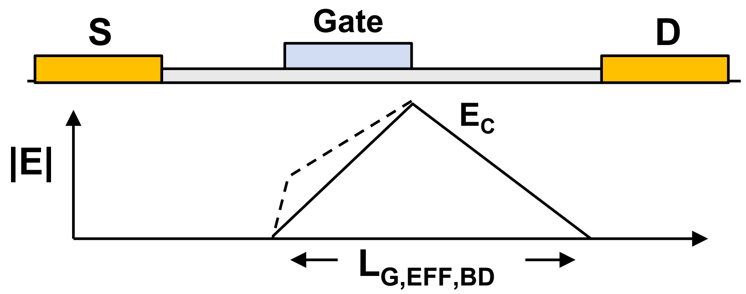


- Uniform, rectangular field profile

→ $V_{MAX} = E_C L_{EFF}$

→ Johnson FOM (for BJTs): $V_{MAX} f_T = \frac{v_{SAT} E_c}{2\pi}$

First-order Johnson/Hollis:

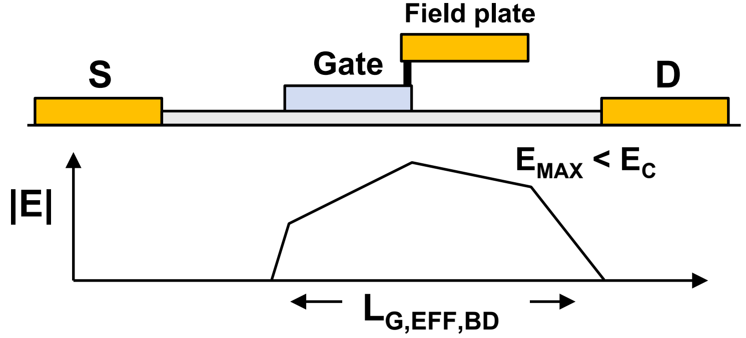


- Triangular field profile, for non-gate-overlapping FETs

→ $V_{MAX} \approx E_C L_{EFF} / 2$

→ Johnson/Hollis FOM for FETs: $V_{MAX} f_T = \frac{v_{SAT} E_c}{4\pi}$

Field-Plated FET:



- Field plate can suppress peak |E|, raise V_{MAX}

→ $E_C L_{EFF} / 2 < V_{MAX} < E_C L_{EFF}$

→ FOM for FETs: $\frac{v_{SAT} E_c}{4\pi} < V_{MAX} f_T < \frac{v_{SAT} E_c}{2\pi}$

- HRL GaN HEMTs* are at 60% of Johnson FOM
  – Also due to AlN barrier and higher quasi-ballistic velocity

$L_{G,EFF,BD}$ = effective gate length at V_{BKDN}

*Y. Tang, *et al.*, *IEEE EDL* 36, 549, 2015

Be Careful with FOMs

HTFOM*

	$\sigma_{thermal}$	Permittivity, ε	E_{crit} , MV/cm	$\sigma_{thermal}$ / (ε E)
Si	145	11.9	~ 0.37	33
GaN	253	10.4	~ 3.4	7.1
Ga_2O_3	11 - 27	10	~ 8.0	0.24
AlN	319	9.8	~ 11.7	2.8
Diamond	3450 (^{12}C)	5.7	~ 10	60

- **Si gets biased toward the "good" by a low E_C**
  - **Not as useful for advanced switching**
- **Important to understand the fundamental physics behind FOMs**

***Huang Thermal FOM in: A. Huang, *IEEE EDL* 25, 298, 2004.**

Summary

- A new power law $E_{crit} \sim E_g^{1.84}$ has been derived for semiconductors based on fitting to normalized measured data
  - Normalized to the non-punch-through condition for $N_D = 1x10^{16}\ cm^{-3}$
- Developed an avalanche model which correlates well
  - Valid for $E_g \geq 0.6$ eV where tunneling is absent
- Historical Johnson FOM only applies to BJTs / HBTs with rectangular E field
  - Can be lower for FETs and even BJTs / HBTs due to non-uniform field profile
  - Partly explains why surface FETs exhibit lower values for Johnson FOM
  - There is not just one Johnson FOM
  - Important to understand the fundamental physics behind FOMs