高頻高压半导世界

_四大金刚的蜘蛛擂台

FoM of Si, GaAs，SiC, and GaN

王不老說半导

四大金刚

- 佛教四大天王→中国的"四大金刚"，为"风调雨顺"的化身
- 东方持国天王掌碧玉琵琶，职调南方增长天王掌青光宝剑，职风西方广目天王掌紫金龙花狐貂，职顺，北方多闻天王掌混元米伞，职雨
- 老上海四大金刚：大饼、油条、豆浆、粢饭
- 那麽納米半导世界呢？

https://buzzly.net/p/4K9jtAHh/

https://kknews.cc/food/3eyg8xa.html

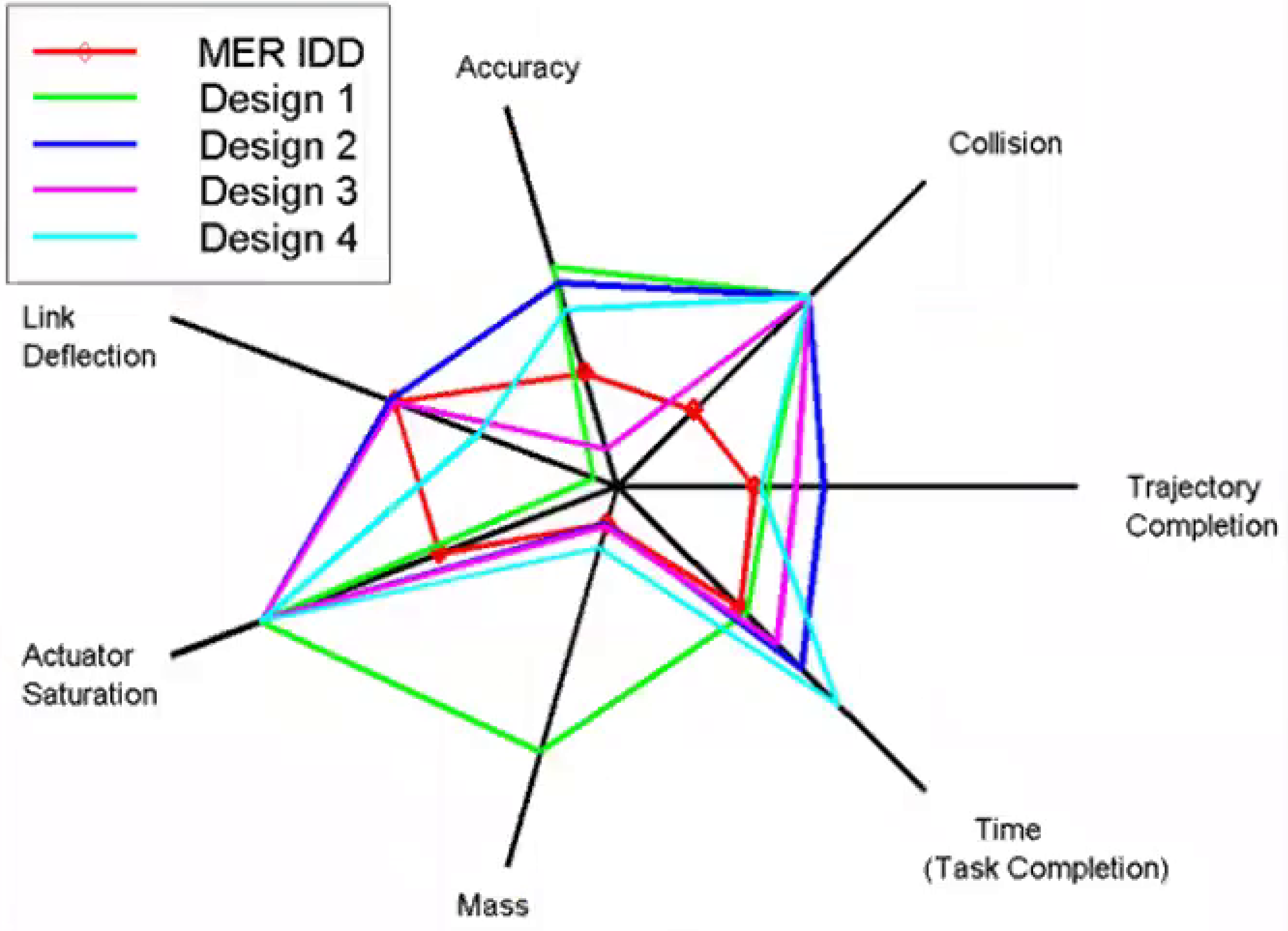
高功率高頻半导江湖的四大金刚

Properties	**Si**	**4H-SiC**	GaAs	GaN	Application
Crystal Structure	Diamond	Hexagonal	Zincblende	Hexagonal	
Energy Gap : E_G (eV)	1.12	3.26 3x	1.43	3.5	high temp. operation, emission wavelength
Electron Mobility: μ_n (cm^2/Vs)	1400	900	8500	1250	High frequency devices
Hole Mobility: μ_p (cm^2/Vs)	600	100	400	200	
Breakdown Field; E_B (V/cm) $x10^6$	0.3	3 10x	0.4	3	Power devices
Thermal Conductivity (W/cmK)	1.5	4.9 3x	0.5	1.3	High heat dissipation
Saturation Drift Velocity: v_S (cm/s) $x10^7$	1	2.7 3x	2	2.7	High frequency devices
Relative Dielectric Constant: ε_S	11.8	9.7	12.8	9.5	
p, n Control	Good	Good	Good	Average	
Thermal Oxide	Good	Good	Behind	Behind	MOS structure

插播: FoM乃是蜘蛛擂台裁判

- FoM = Figure-of-Merit = 品質因數 = 蜘蛛擂台上的裁判
  - 產品優劣比較，必須上此擂台一較長短
  - 只是吹噓自己，不敢上蜘蛛擂台者，必是个大忽悠
- 各派上台比優劣，秀風騷，孰強孰弱?一目了然

Radar chart: 雷达图;蜘蛛网图

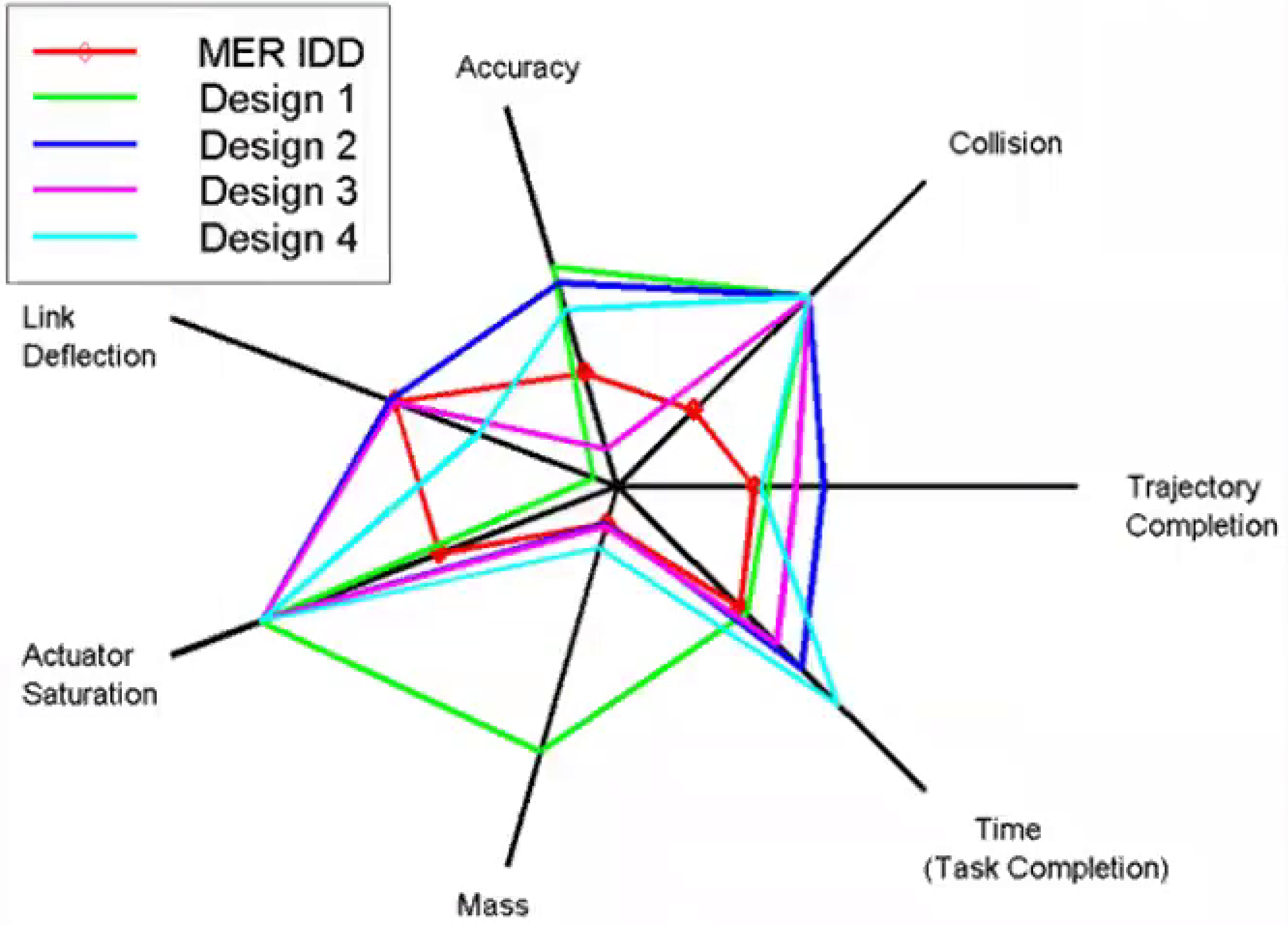


By NASA Primary START - Automation Tool for Rapid Design of Space Systems, Public Domain

插播: FoM乃是蜘蛛擂台裁判

- **FoM = Figure-of-Merit =** 品質因數 = 蜘蛛擂台上的裁判
  - 產品優劣比較，必須上此擂台一較長短
  - 只是吹噓自己，不敢上蜘蛛擂台者，必是个大忽悠
- 各派上台比優劣，秀風騷，孰強孰弱?一目了然

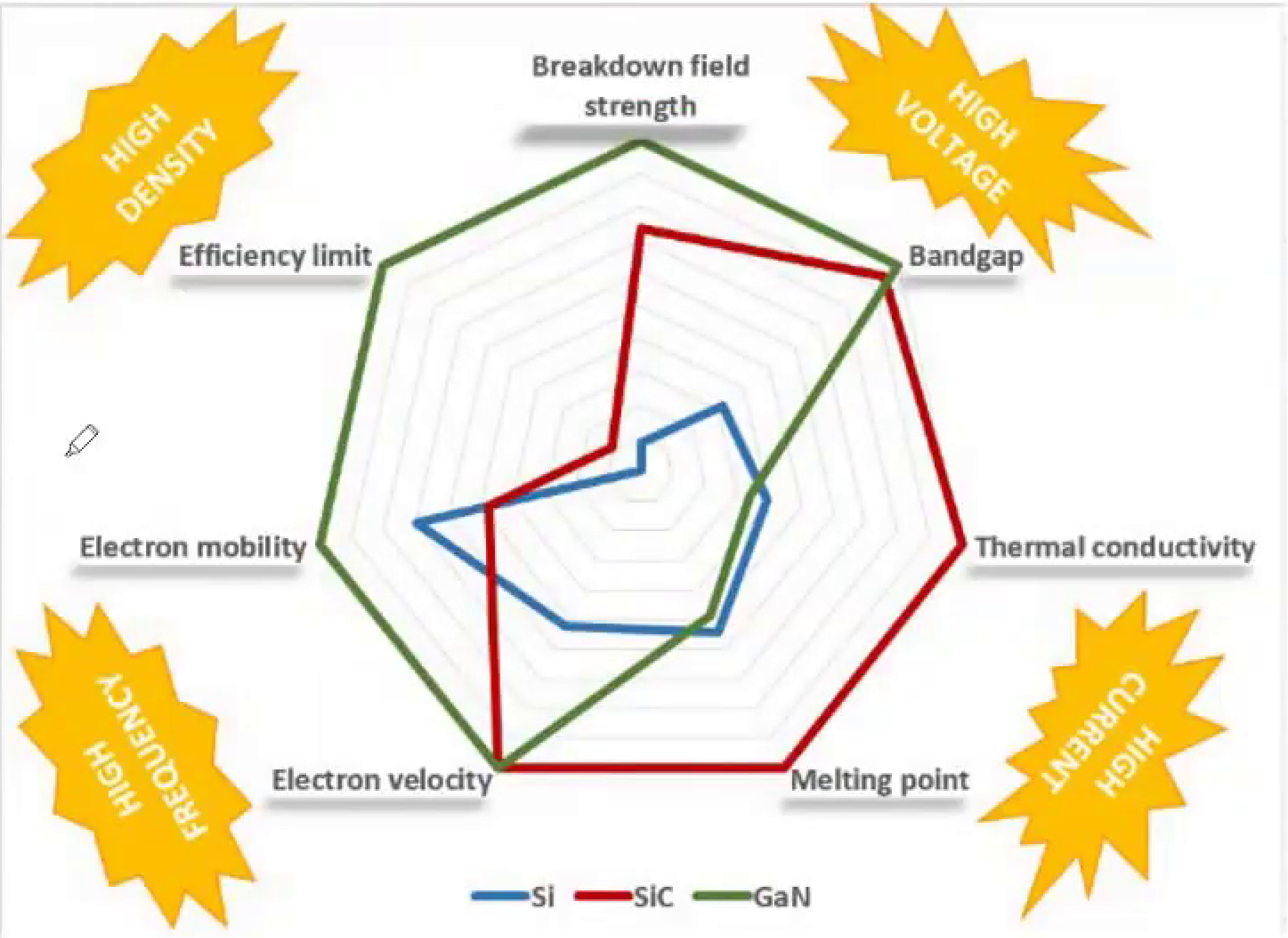
Radar chart: 雷达图;蜘蛛网图



By NASA Primary START - Automation Tool for Rapid Design of Space Systems, Public Domain

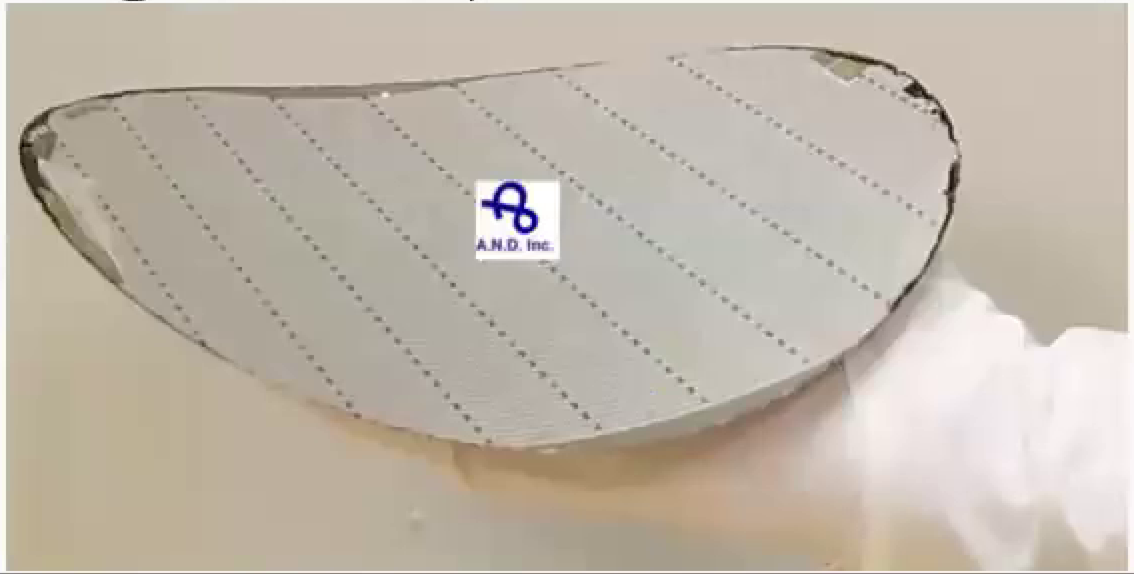
Si, SiC and GaN的蜘蛛擂台

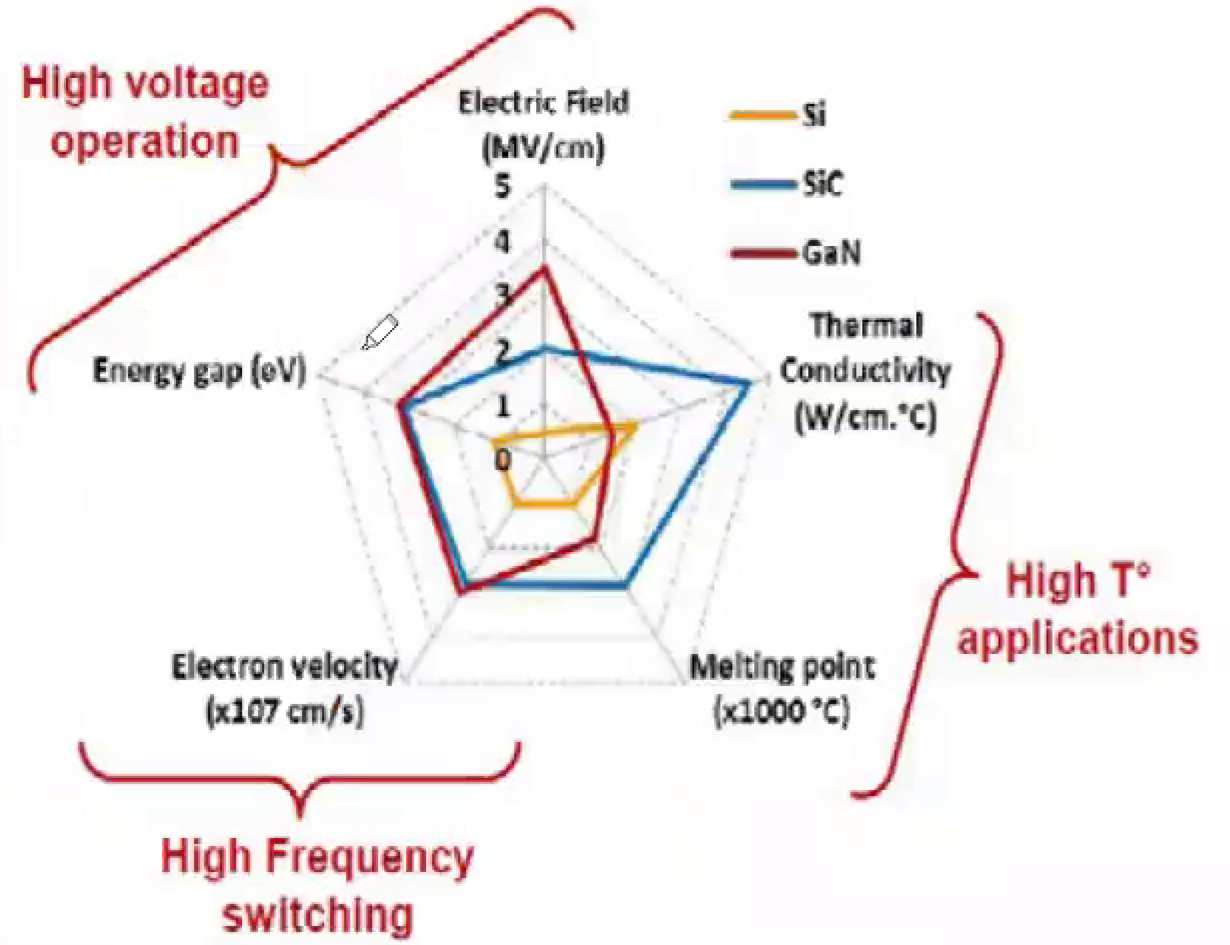
- 比較各家材料本身的特質，自然是各有所長，也各有所短



Si, SiC and GaN的蜘蛛擂台

- SiC for high Temp application
- GaN ~ reach high voltage, but requires bulk GaN substrate
- Silicon may not compete at the high frequency range (but AND begs to differ)





Imbrugliaet al (2019). WINSIC4AP: HIGH PERFORMANCE SIC POWER TECHNOLOGY FOR RELIABLE APPLICATIONS

試問: 如何找出Si, GaAs and GaN的FoM?

- 解答:為了避免各說各話，必須找出一個可以綜合相關參數的蜘蛛擂台裁判(FoM)如下:

1. 先找出個墊底的(Si)
2. 再找出你認為重要的相關參數集
3. FoM = $\dfrac{\text{新材料參數集}}{\text{墊底的硅參數集}}$

   - Johnson (低壓考量) = $\dfrac{\mathrm{v}E_{crit}}{(\mathrm{v}E_{crit})_{Si}}$
   - Baliga (加碼高頻) = $\dfrac{\mu E^2{}_{crit}}{(\mu E^2{}_{crit})_{Si}}$

   (E_{crit} 重要性被加權了)

	Si	GaAs	GaN
Bandgap (eV)	1.1	1.42	3.4
Critical field, E_{crit} (MV/cm)	0.3	0.4	3.3
Mobility, μ (cm^2/V/s)	1350	8500	2000
Peak velocity, v_{peak} (10^7 cm/s)	1	2	2.5
Baliga FOM $\propto \mu * E_{crit}^2$ (normalized to Si)	1	11	179
Johnson FOM $\propto v_{peak} * E_{crit}$ (normalized to Si)	1	2.7	27.5

Table I: Baliga and Johnson FOMs for Si, GaAs and GaN. GaN has the highest FOMs making it advantageous for high voltage and RF.

B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," EDL, 10(10), pp. 455-457, 1989

試問: 如何找出Si, GaAs and GaN的FoM?

- 解答:但FoM會隨時空改變
  1. 現代芯片由於縮放比例(scaling)越來越小，許多熱傳甚至電性，都可能不一樣了，例如GaAs在變小以後，DOS (become discrete)竟然不夠，μ，v的優勢變小
  2. 最終，當然是整體成本性能考量(i.e., PPAC)才是幕後大老闆

	Si	GaAs	GaN
Bandgap (eV)	1.1	1.42	3.4
Critical field, E_{crit} (MV/cm)	0.3	0.4	3.3
Mobility, μ ($cm^2/V/s$)	1350	8500	2000
Peak velocity, v_{peak} (10^7 cm/s)	1	2	2.5
Baliga FOM $\propto \mu * E_{crit}^2$ (normalized to Si)	1	11	179
Johnson FOM $\propto v_{peak} * E_{crit}$ (normalized to Si)	1	2.7	27.5

Table I: Baliga and Johnson FOMs for Si, GaAs and GaN. GaN has the highest FOMs making it advantageous for high voltage and RF.

B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," EDL, 10(10), pp. 455-457, 1989

試問: GaN的Baliga FoM為何?

- 解答:
- Baliga FoM = $\frac{\mu E^2{}_{crit}}{(\mu E^2{}_{crit})_{Si}} = \frac{2000\times3.3^2}{1350\times0.3^2} =$ 179
- 然而，Baliga又在其最新2019著作將以上公式改了(E_{crit}更重)
- Baliga FoM (2019) = $\frac{\varepsilon\mu E^3{}_{crit}}{(\varepsilon\mu E^3{}_{crit})_{Si}} = \frac{9.5\times2000\times3.3^3}{11.7\times1350\times0.3^3}$ = 1601 (**Mamamia, 好大**)

	Si	GaAs	GaN
Bandgap (eV)	1.1	1.42	3.4
Critical field, E_{crit} (MV/cm)	0.3	0.4	3.3
Mobility, μ ($cm^2/V/s$)	1350	8500	2000
Peak velocity, v_{peak} (10^7 cm/s)	1	2	2.5
Baliga FOM $\propto \mu^* E_{crit}^2$ (normalized to Si)	1	11	179
Johnson FOM $\propto v_{peak}{}^* E_{crit}$ (normalized to Si)	1	2.7	27.5

Table I: Baliga and Johnson FOMs for Si, GaAs and GaN. GaN has the highest FOMs making it advantageous for high voltage and RF.

B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," EDL, 10(10), pp. 455-457, 1989

Fundamentals of Power Semiconductor Devices, B. J. Baliga, 2019

試問: GaN的Baliga FoM為何?

- 解答:
- Baliga FoM = $\frac{\mu E^2{}_{crit}}{(\mu E^2{}_{crit})_{Si}} = \frac{2000\times3.3^2}{1350\times0.3^2} =$ 179
- 然而，Baliga又在其最新2019著作將以上公式改了(E_{crit}更重)
- Baliga FoM (2019) = $\frac{\varepsilon\mu E^3{}_{crit}}{(\varepsilon\mu E^3{}_{crit})_{Si}} = \frac{9.5\times2000\times3.3^3}{11.7\times1350\times0.3^3}$ = 1601 (**Mamamia, 好大**)

	Si	GaAs	GaN
Bandgap (eV)	1.1	1.42	3.4
Critical field, E_{crit} (MV/cm)	0.3	0.4	3.3
Mobility, μ (cm²/V/s)	1350	8500	2000
Peak velocity, v_{peak} (10^7 cm/s)	1	2	2.5
Baliga FOM $\propto \mu^* E_{crit}^2$ (normalized to Si)	1	11	179
Johnson FOM $\propto v_{peak}{}^* E_{crit}$ (normalized to Si)	1	2.7	27.5

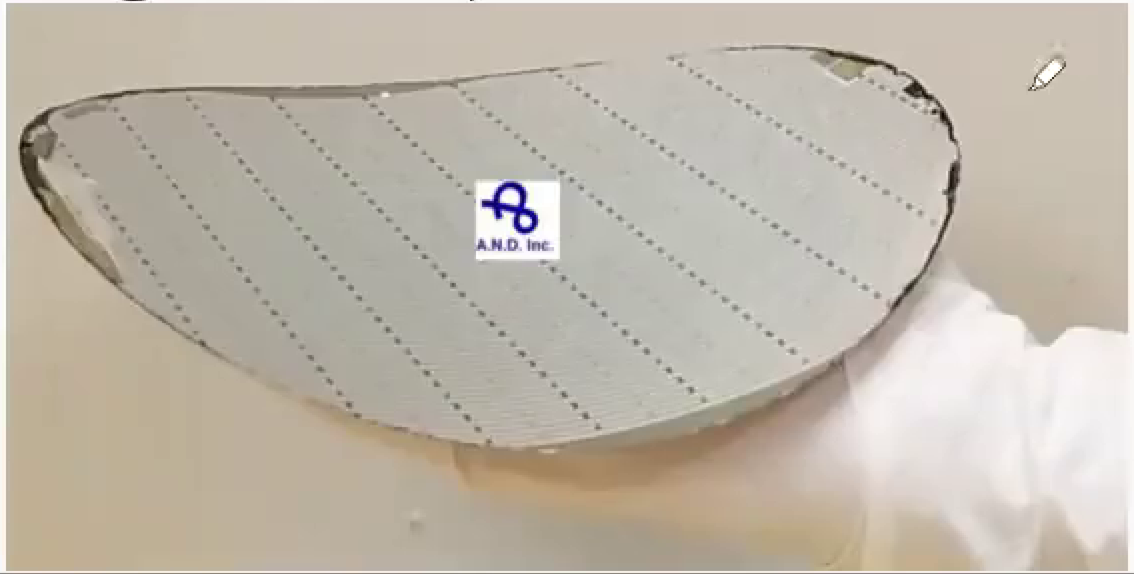
Table I: Baliga and Johnson FOMs for Si, GaAs and GaN. GaN has the highest FOMs making it advantageous for high voltage and RF.

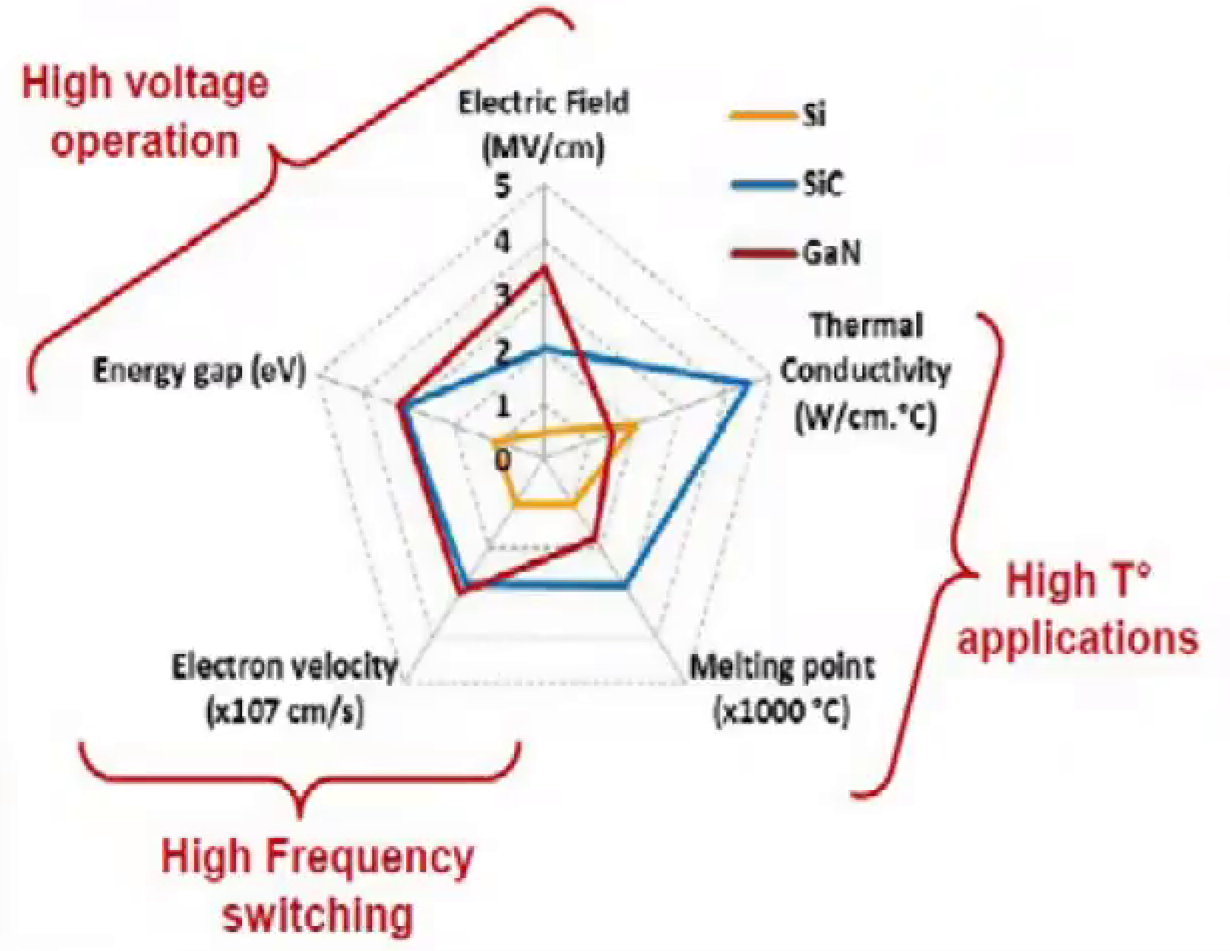
B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," EDL, 10(10), pp. 455-457, 1989

Fundamentals of Power Semiconductor Devices, B. J. Baliga, 2019

Si, SiC and GaN的蜘蛛擂台

- SiC for high Temp application
- GaN ~ reach high voltage, but requires bulk GaN substrate
- Silicon may not compete at the high frequency range (but AND begs to differ)





Imbrugliaet al (2019). WINSIC4AP: HIGH PERFORMANCE SIC POWER TECHNOLOGY FOR RELIABLE APPLICATIONS

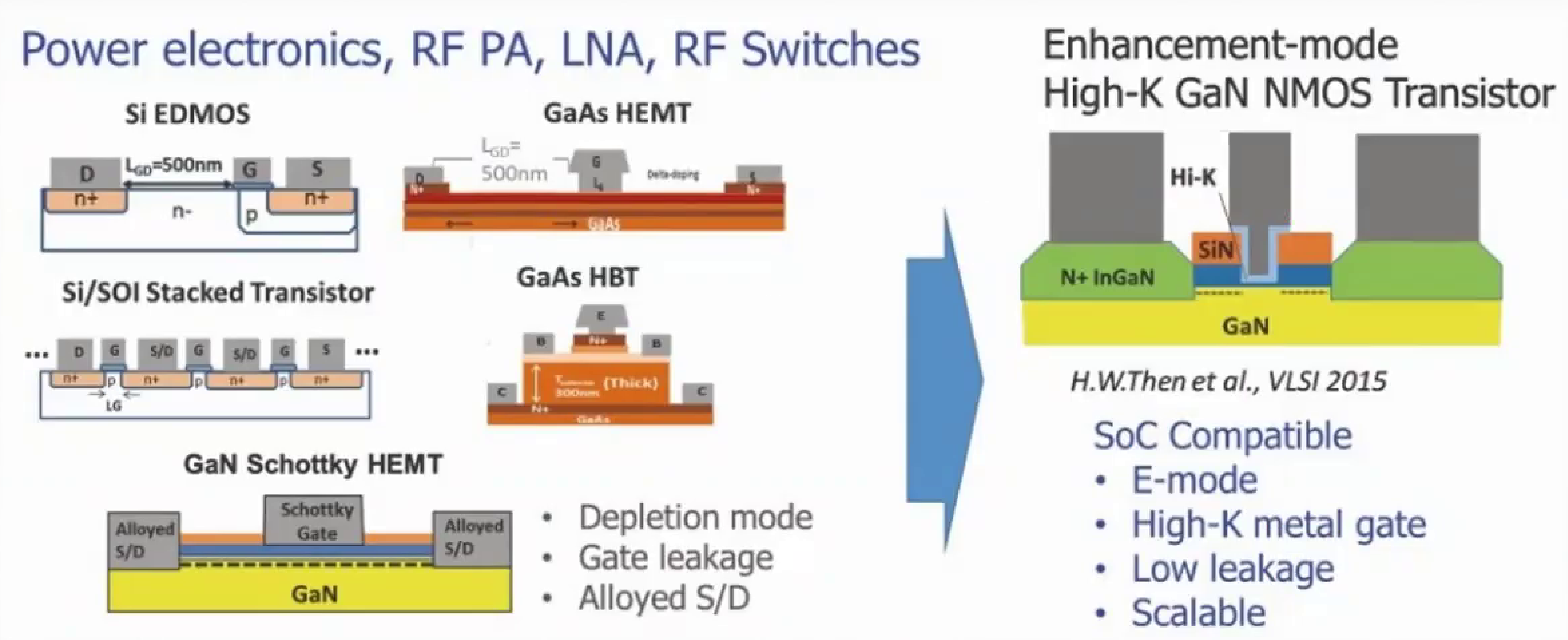
目前四大金刚半导板塊仍動盪不安

- 代有能人輩出，各板塊並非固定，隨時有對手虎視眈眈，欲取而代之
- 其實若是能用老朋友硅，因其技術非常成熟，大家還是願意用他的
- 最近有一家初創公司(AND，applied novel devices)宣稱其硅半导產品，竟可以其超薄体特色(30um)侵蝕GaN與SiC部分市場

https://www.powerelectronicsnews.com/new-silicon-power-mosfet-technology-rivals-gan-with-near-zero-reverse-recovery-and-low-on-resistance/

預告:英特爾想要以GaN一統功率半导江山

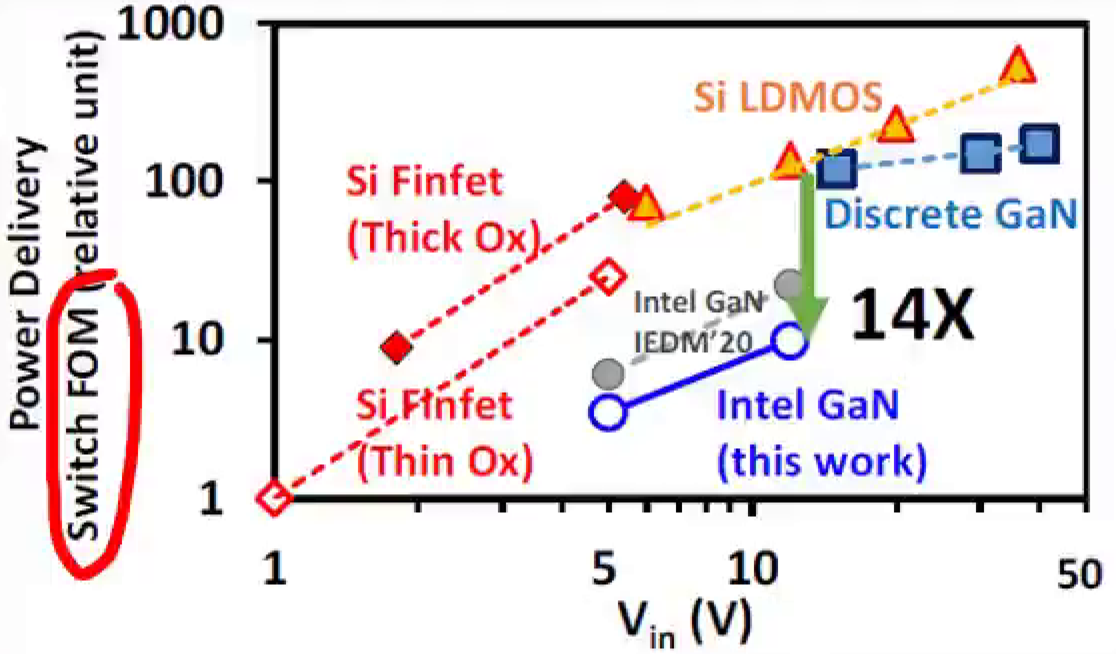
- 英特爾以為左下各式功率半导皆可由HKMG的GaN MOS取代

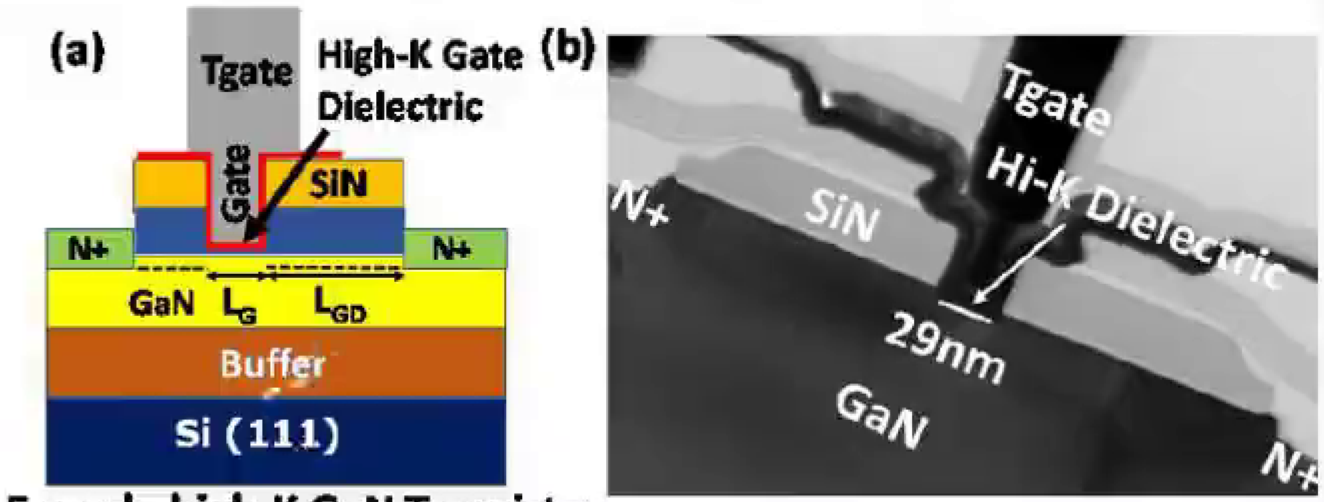


https://compoundsemiconductor.net/article/111291/Stacking_GaN_and_silicon_transistors_on_300_mm_silicon/feature

預告:英特爾想要以GaN一統功率半导江山

- CR (Then等) 已經研究十年
- 世界第一個做到 HKMG GaN-nMOS on 300mm-Si(111)





E-mode high-K GaN Transistor

Fig.1 (a) schematic of the E-mode high-k gate dielectric GaN transistor of this work, (b) TEM micrographs of the E-mode high-k GaN transistors of this work showing short channel length of 29nm.

H. W. Then et al., "Advanced Scaling of Enhancement Mode High-K Gallium Nitride-on-300mm-Si(111) Transistor and 3D Layer Transfer GaN-Silicon Finfet CMOS Integration," IEDM'21, 11.1.1

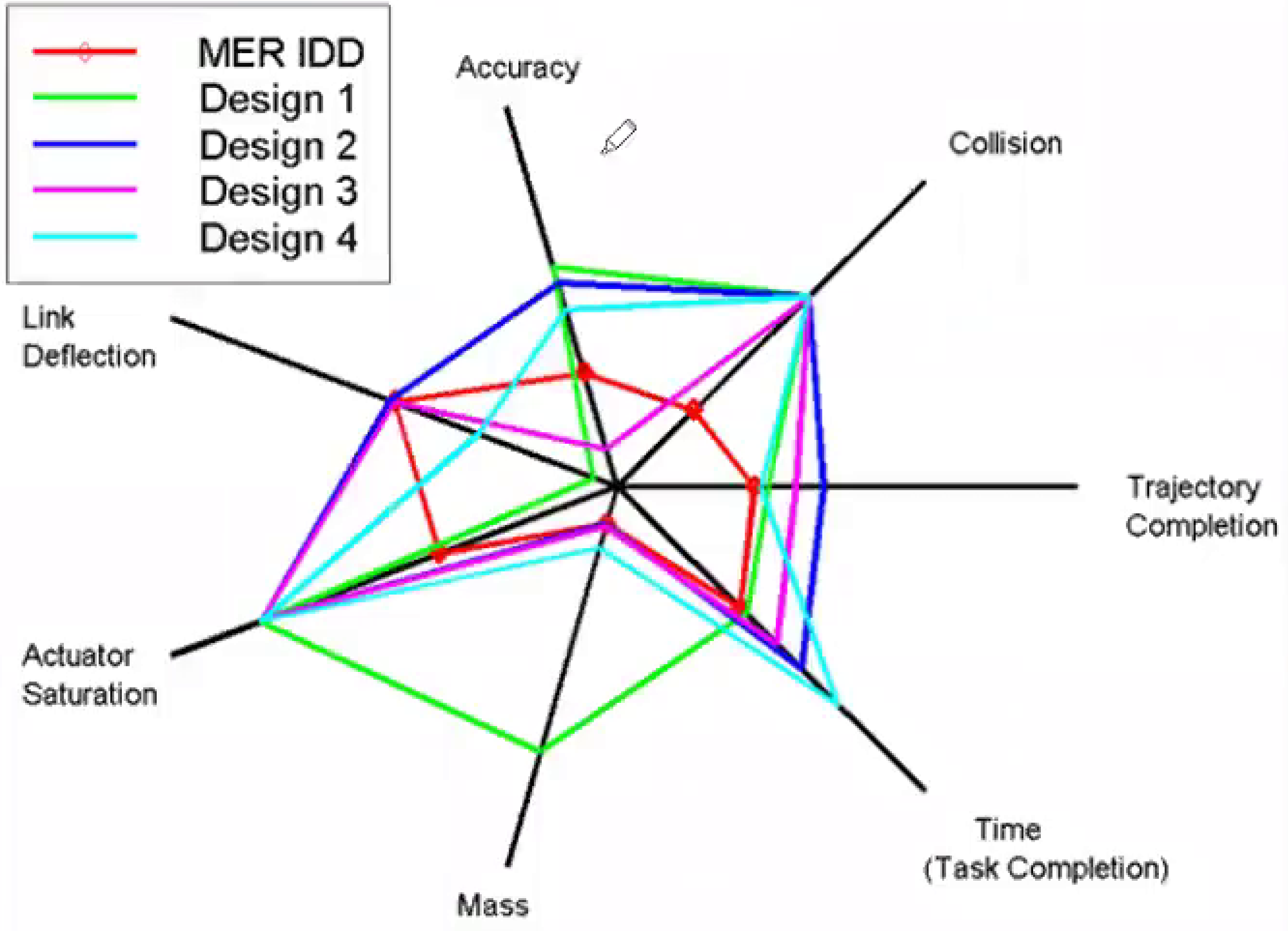
高功率高頻半导江湖的四大金刚

Properties	Si	4H-SiC	GaAs	GaN	Application
Crystal Structure	Diamond	Hexagonal	Zincblende	Hexagonal	
Energy Gap : E_G (eV)	1.12	3.26 3x	1.43	3.5	high temp. operation, emission wavelength
Electron Mobility: μ_n (cm^2/Vs)	1400	900	8500	1250	High frequency devices
Hole Mobility: μ_p (cm^2/Vs)	600	100	400	200	
Breakdown Field; E_B (V/cm) $x10^6$	0.3	3 10x	0.4	3	Power devices
Thermal Conductivity (W/cmK)	1.5	4.9 3x	0.5	1.3	High heat dissipation
Saturation Drift Velocity: v_S (cm/s) $x10^7$	1	2.7 3x	2	2.7	High frequency devices
Relative Dielectric Constant: ε_S	11.8	9.7	12.8	9.5	
p, n Control	Good	Good	Good	Average	
Thermal Oxide	Good	Good	Behind	Behind	MOS structure

插播: FoM乃是蜘蛛擂台裁判

- FoM = Figure-of-Merit = 品質因數 = 蜘蛛擂台上的裁判
  - 產品優劣比較，必須上此擂台一較長短
  - 只是吹噓自己，不敢上蜘蛛擂台者，必是个大忽悠
- 各派上台比優劣，秀風騷，孰強孰弱?一目了然

Radar chart: 雷达图;蜘蛛网图



By NASA Primary START - Automation Tool for Rapid Design of Space Systems, Public Domain

試問: 如何找出Si, GaAs and GaN的FoM?

- 解答:為了避免各說各話，必須找出一個可以綜合相關參數的蜘蛛擂台裁判(FoM)如下:

1. 先找出個墊底的(Si)
2. 再找出你認為重要的相關參數集
3. FoM = $\dfrac{\text{新材料參數集}}{\text{墊底的硅參數集}}$

   - Johnson (低壓考量) = $\dfrac{\mathrm{V}E_{crit}}{(\mathrm{V}E_{crit})_{Si}}$
   - Baliga (加碼高頻) = $\dfrac{\mu E^2{}_{crit}}{(\mu E^2{}_{crit})_{Si}}$

   (E_{crit} 重要性被加權了)

	Si	GaAs	GaN
Bandgap (eV)	1.1	1.42	3.4
Critical field, E_{crit} (MV/cm)	0.3	0.4	3.3
Mobility, μ (cm²/V/s)	1350	8500	2000
Peak velocity, v_{peak} (10^7 cm/s)	1	2	2.5
Baliga FOM $\propto \mu^* E_{crit}{}^2$ (normalized to Si)	1	11	179
Johnson FOM $\propto v_{peak}{}^* E_{crit}$ (normalized to Si)	1	2.7	27.5

Table I: Baliga and Johnson FOMs for Si, GaAs and GaN. GaN has the highest FOMs making it advantageous for high voltage and RF.

B. J. Baliga, "Power semiconductor device figure of merit for high-frequency applications," EDL, 10(10), pp. 455-457, 1989