What's here and what's coming in wide bandgap power semiconductor transistors

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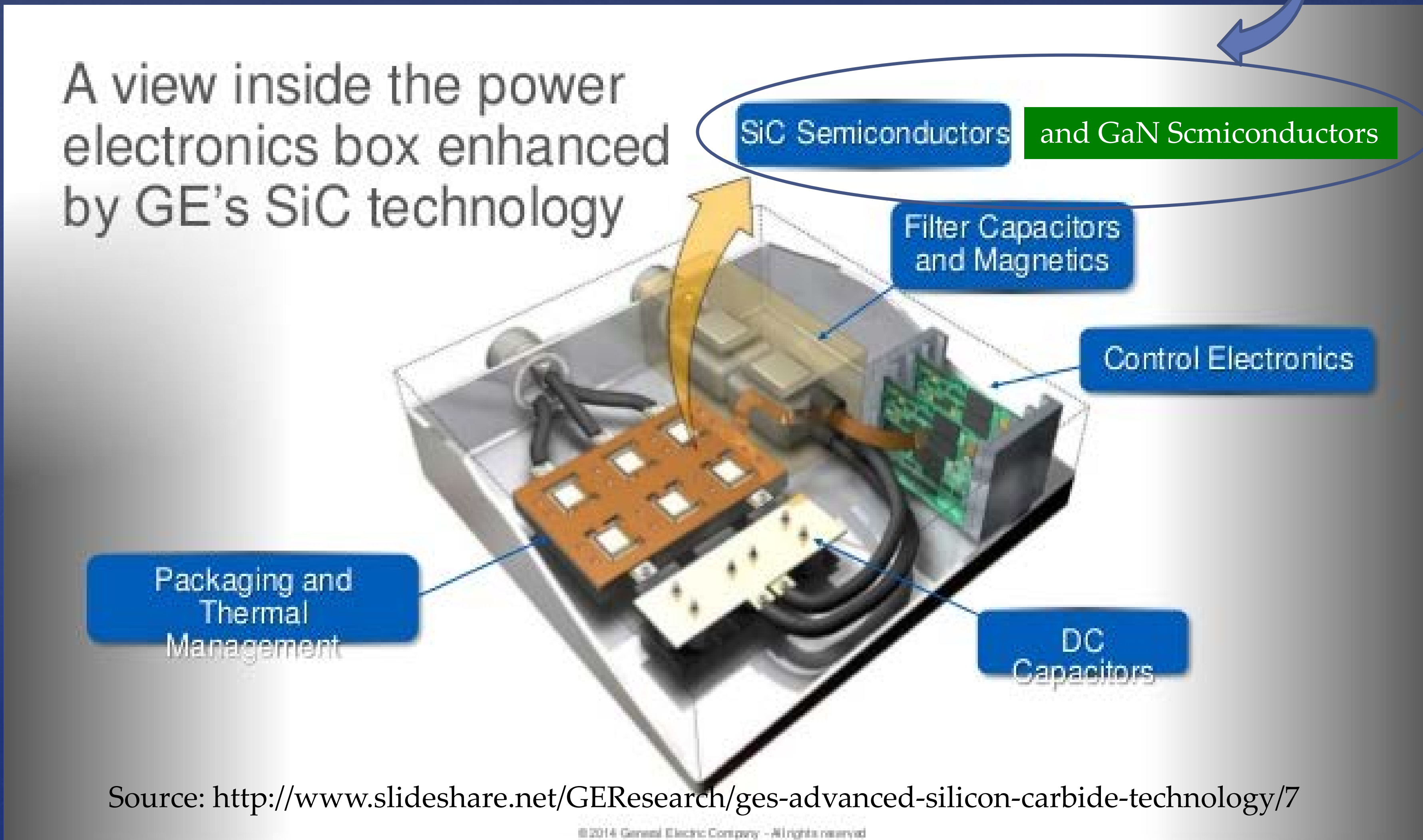
Wide BandgapTransistors are an Enabling Technology



Source: http://www.slideshare.net/GEResearch/ges-advanced-silicon-carbide-technology/7

Today's Topics

"Wide Bandgap Semiconductors (WBGs)" – What's special/unique about these materials?

What does a WBGS power transistor look like? Basic operating principles…

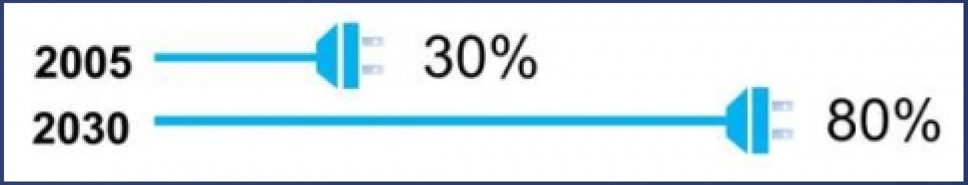
Who's building/supplying these devices? What's their status?

What's coming … new technologies?

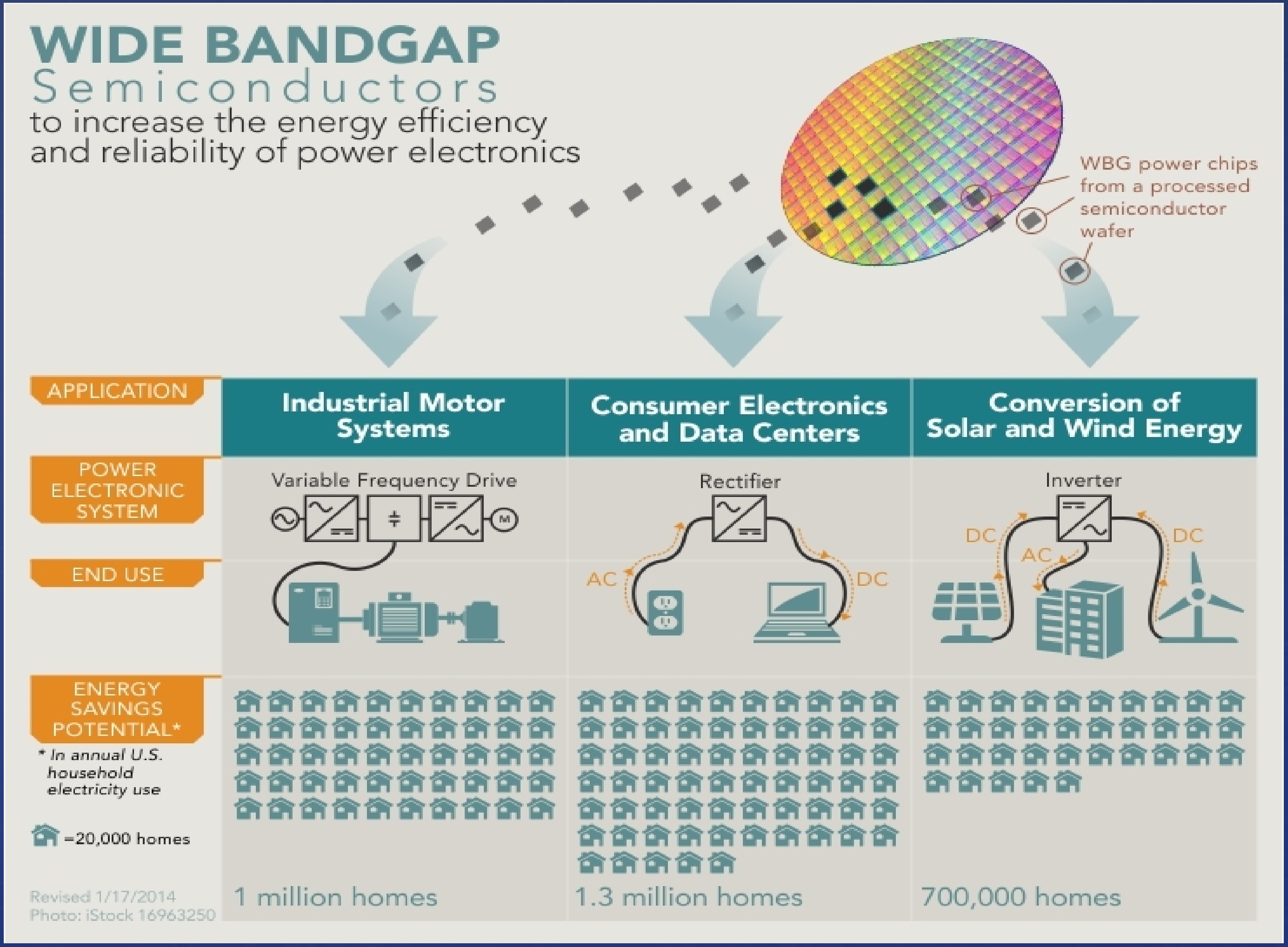
Disclaimer: Despite numerous slides from other organizations/companies, these are not intended to promote any of these; but are used only for illustrative purposes.

DOE-EERE "Power America" Program

Percent of all electricity flowing through power semiconductors



Anticipated Impact of WBG Semiconductors



A Bit of Semiconductors

The Upper Right-Hand Corner of the Periodic Table of Elements

II	III	IV	V	VI
	B	C	N	
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In		Sb	Te

… from which the elements of most of the more common semiconductor materials come

… including Group IV Elemental Semiconductors – silicon (Si) and germanium (Ge) but ALSO compound semiconductor – silicon carbide (SiC) ➔ Covalent tetrahedral bonds

… but similar covalent tetrahedral bonds can be found in Group III-V Compound Semiconductors – *gallium nitride (GaN)*

Simple Comparisons of Selected Semiconductors

Material	μ_e	ε	Eg	BFOM Ratio	JFM Ratio	Tmax
Si	1300	11.4	1.1	1.0	1.0	300 C
GaAs	5000	13.1	1.4	9.6	3.5	300 C
SiC	260	9.7	2.9	3.1	60	600 C
GaN	1500	9.5	3.4	24.6	80	700 C

WBG

Key Advantages

BFOM = Baliga's figure of merit for power transistor performance [K*μ*Ec³]
JFM = Johnson's figure of merit for power transistor performance (High frequency/microwave)
(Breakdown, electron velocity product) [Eb*Vbr/2π]

Power Semiconductor Figures of Merit

- Switching loss power as function of transistor area (simplified)

$$P_{\text{loss}}(A) = \frac{r_{\text{ds,on}}}{A} \cdot I_{\text{D,rms}}^2 + I_{\text{D}} V_{\text{D}} \frac{q_{\text{sw}} A}{I_{\text{G}}} f$$

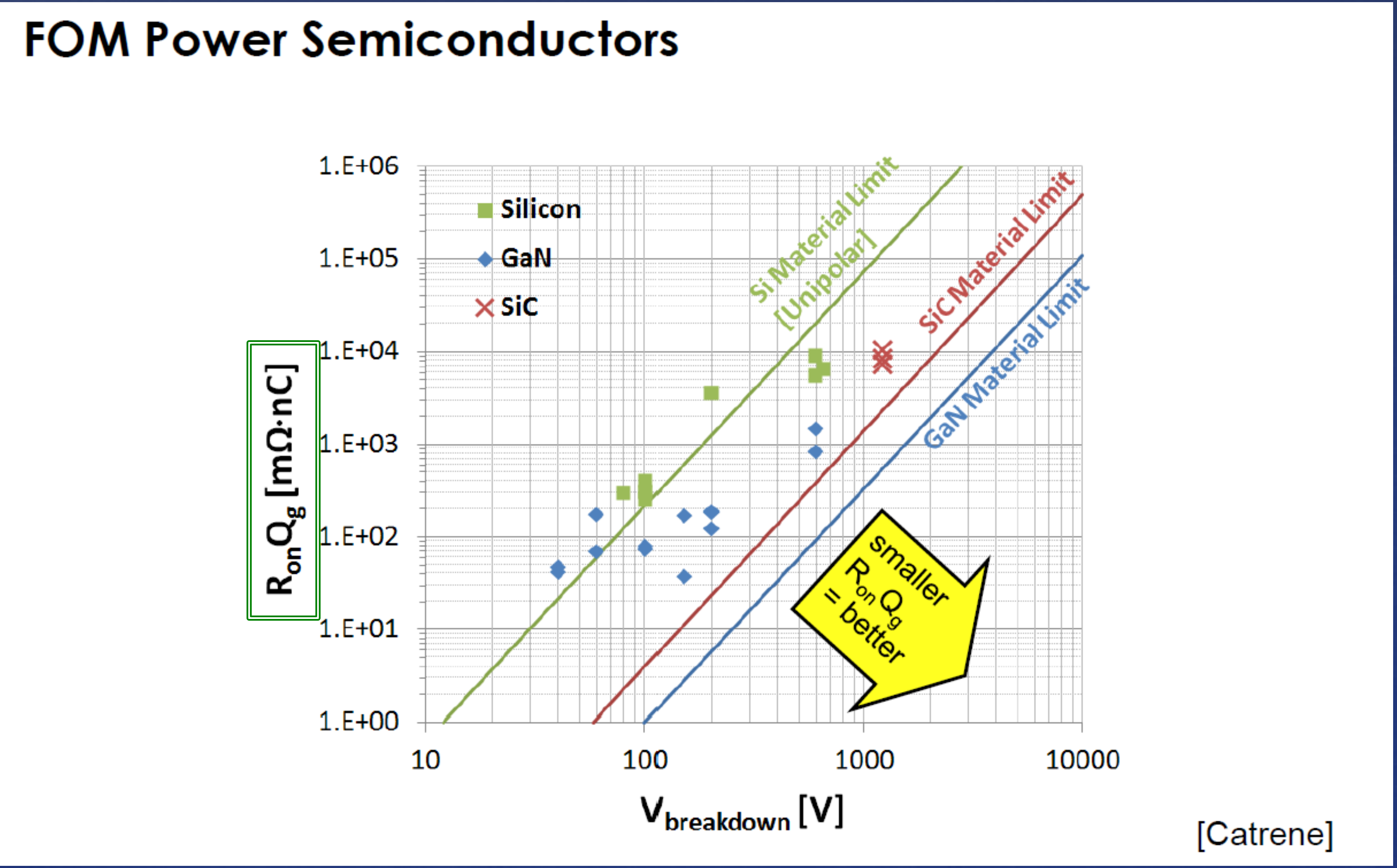
- Minimum switching loss

$$P_{\text{loss,min}} = 2 I_{\text{D,rms}} \sqrt{\frac{I_{\text{D}} V_{\text{D}} f}{I_{\text{G}}}} \cdot \sqrt{R_{\text{ds,on}} Q_{\text{sw}}}$$

- Semiconductor-related loss term (= FOM)

$$R_{\text{ds,on}} Q_{\text{sw}}$$

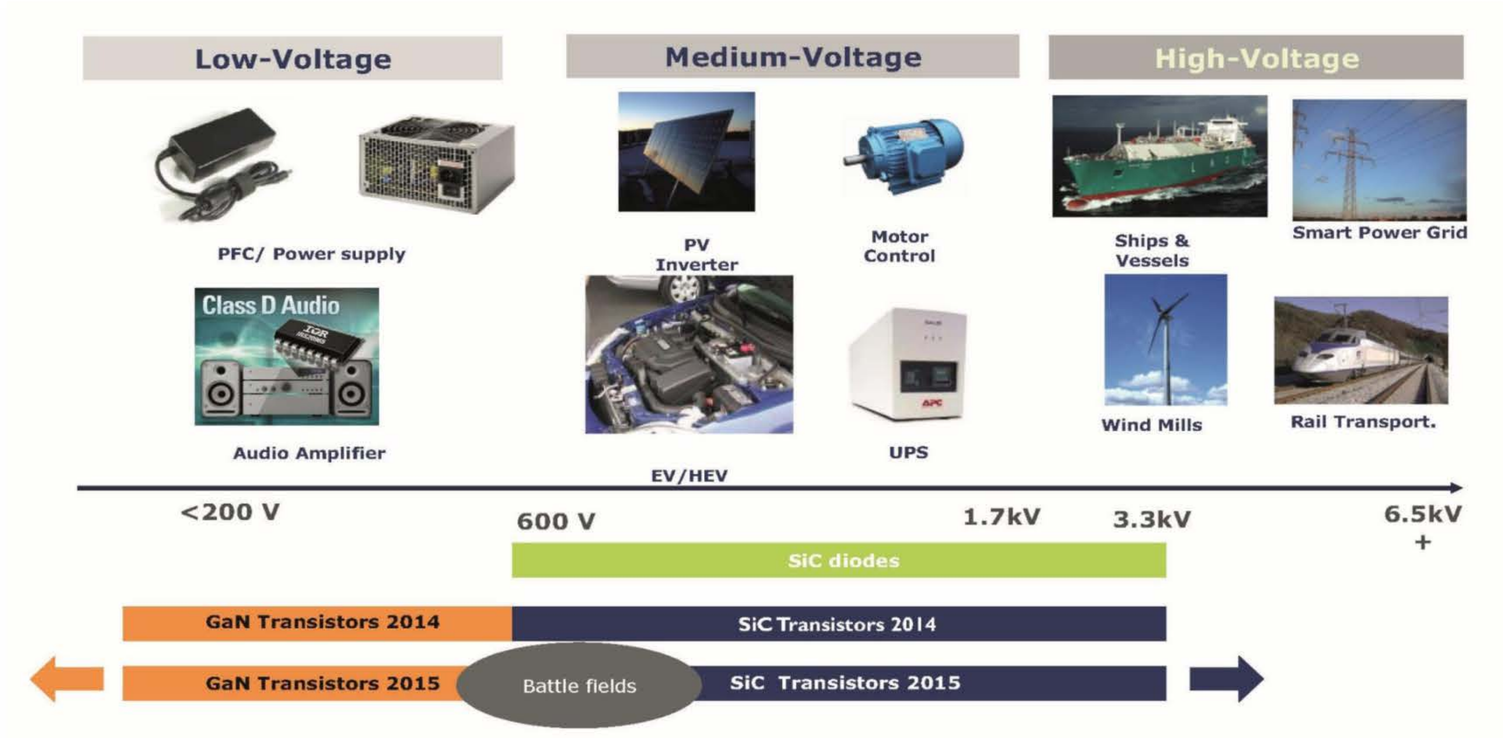
Figure of Merit Comparison of Power Semiconductor Technologies



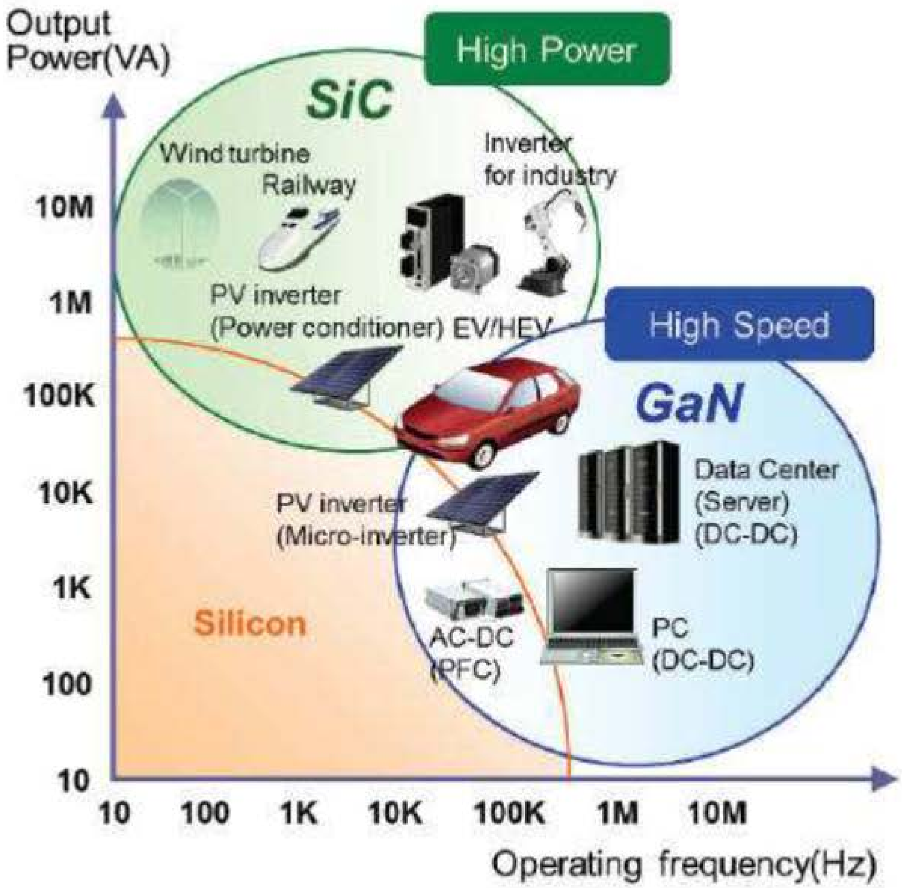
WBG MARKET SEGMENTATION – GAN VS. SIC AS A FUNCTION OF VOLTAGE RANGE

(Source: GaN and SiC for power electronics applications report, Yole Développement, July 2015)

Will GaN and SiC compete for the same power electronics applications? (Source: Yole Développement)



Applications and Technologies



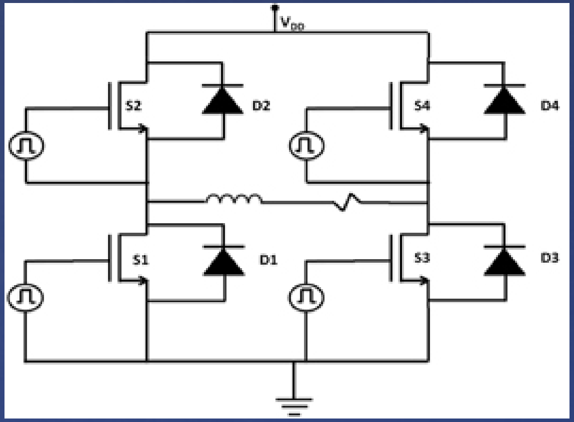
SiC for high power voltages (>1kV) with high current
= niche market

GaN on Si for high frequency at midrange voltages (<1kV, up to 100A)
= mass market

Source: „GaN-on-Si power transistors from French lab Leti", CEA-Leti
http://www.electronicsweekly.com/news/design/power/gan-on-si-power-transistors-french-lab-leti-2015-07/

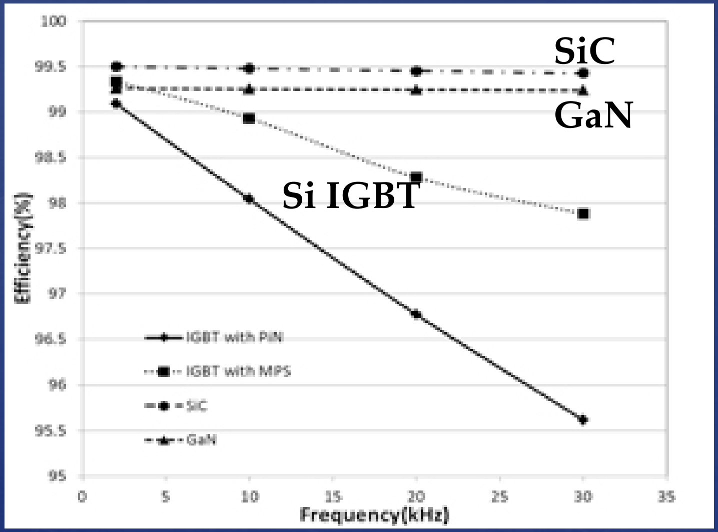
Transistor Technology Comparison Performance vs. Frequency

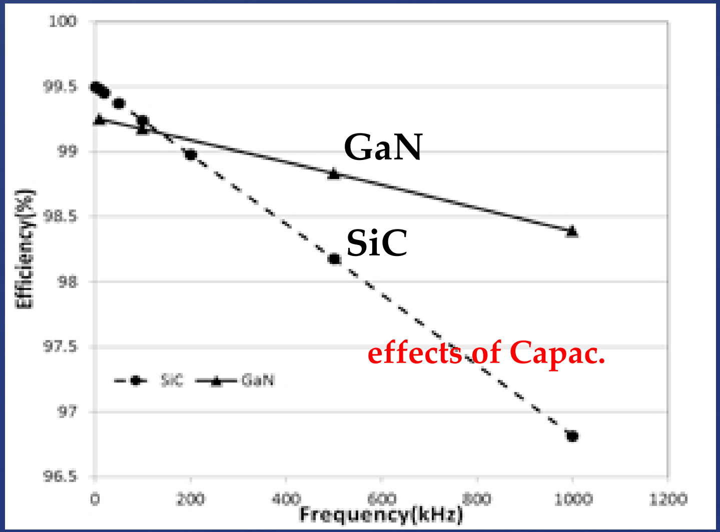
Source: CPES, Va Tech. http://www.cpes.vt.edu/public/nugget/2013_D1.1.php



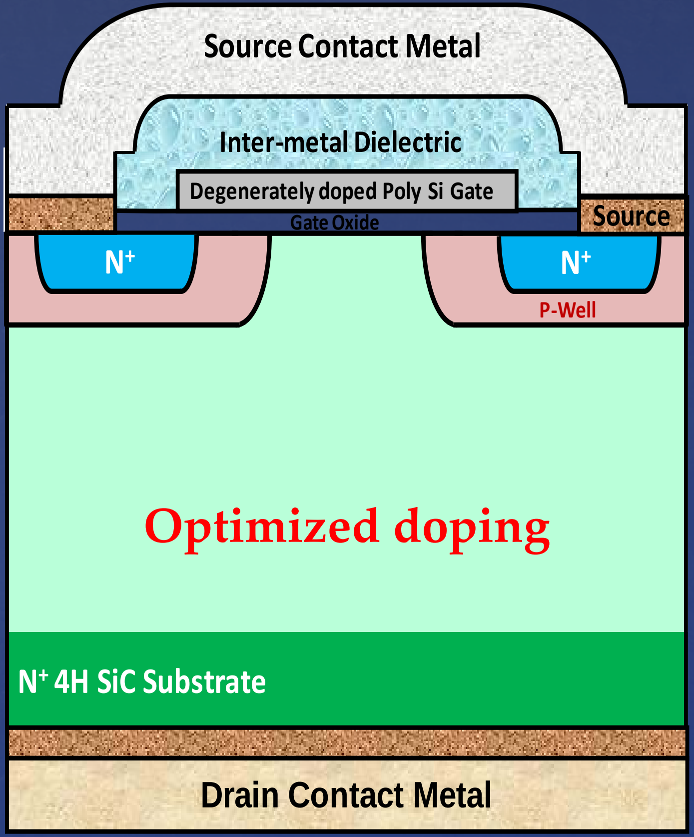
SPICE Simulation of Full Bridge Inverter

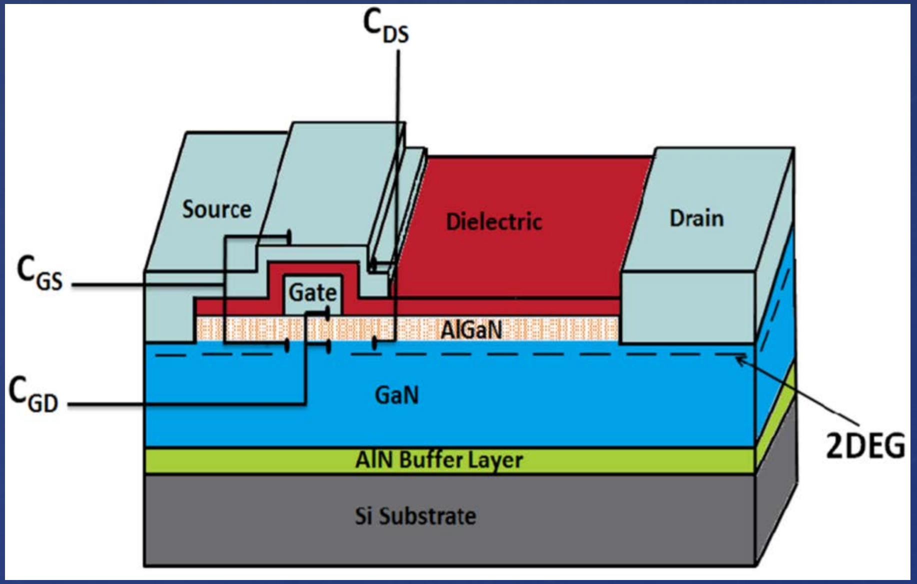
- 1200 V SiC vertical DMOSFET (Cree)
- 3 series 200 V GaN lateral HFET (EPC)





WBG Transistor Structure Comparison





Cree Gen 3 DMOS
Vertical device

EPC GaN HFET
Lateral device

Source: Cree Power – Sept 2014 HMW Direct-Drive Motor Workshop

Source: GaN Transistors for Efficient Power Conversion, A. Lidow, et al. Power Conversion Publns., 2012.

Other Advantages of WBGs Transistors

Higher Temperature Operation (≥ 150°C more than Si)➔

- Reduced Requirements for Cooling System – Less Area, Less Cost
- Improved Reliability Under Harsh Operating Conditions

Higher Switching Frequency (≥ 10X more than Si)➔

- Lower Switching Losses – Better Efficiency
- Smaller Area Required for Capacitors and Inductors

Greater Power Density (≥ 2X more than Si)➔

Bottom Line: Opportunity for Smaller, Less costly, More Efficient, More Reliable Power Electronics

"SiC and GaN power market to grow by factor of 17 during the next decade

THE EMERGING MARKET for SiC and GaN power semiconductors is forecast to grow by a factor of 17, during the next 10 years, energised by growing demand for

- power supplies
- hybrid and electric vehicles
- photovoltaic (PV) inverters
- other established applications (e.g. variable speed motor drives).

Worldwide revenue from sales of SiC and GaN power semiconductors is projected to rise to $2.5 billion in 2023, up from just $150 million in 2013, according to 'The World Market for SiC & GaN Power Semiconductors - 2014 Edition' a new report from IHS Inc."

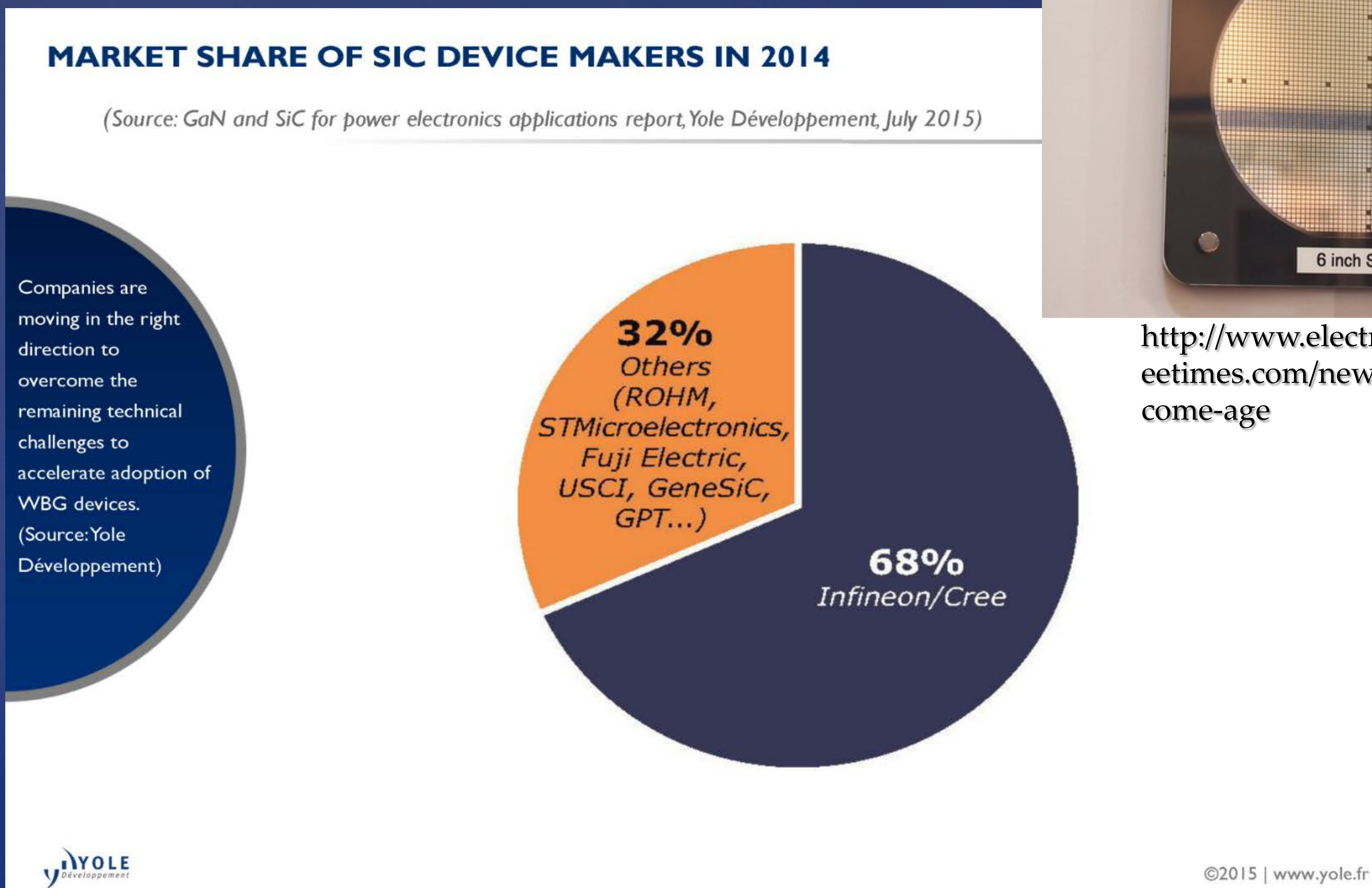
From ***Compound Semiconductor***, April/May 2015; www.compoundsemiconductor.net

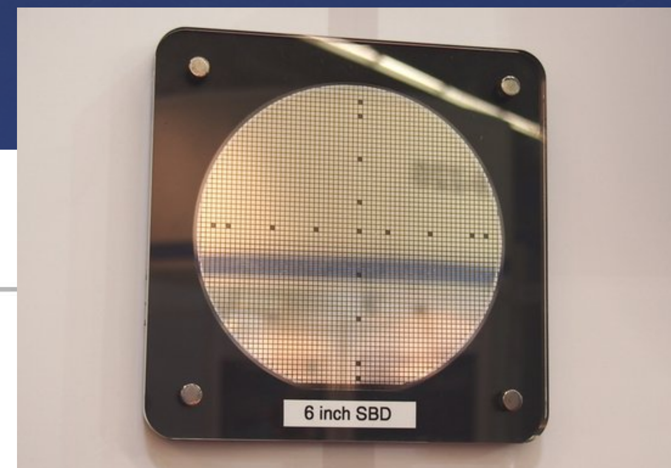
Note: LED lighting market expected to be $42B by 2019

Companies Producing SiC Power Transistors (various types)

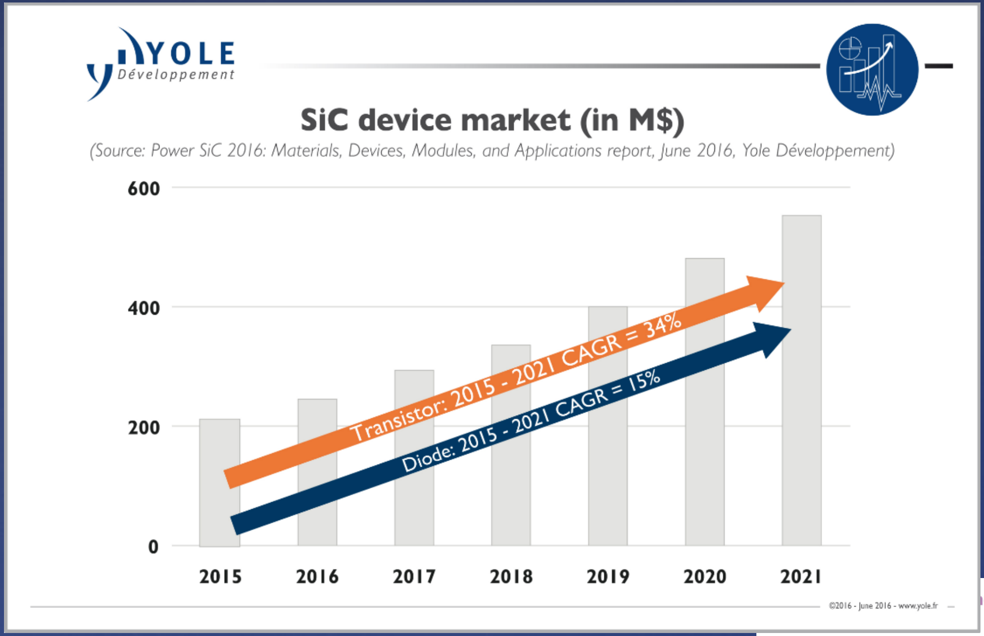
- Infineon Technologies AG (formerly Wolfspeed, formerly CREE of Durham, NC), Neubiberg, Germany
- GeneSiC Semiconductor, Dulles, VA
- STMicroelectronics NV, Geneva, Switzerland
- ROHM Semiconductor, Kyoto, Japan
- TranSiC AB, Kista, Sweden
- IXYS, Milpitas, CA
- APEI, Fayetteville, AR
- Powerex, Youngwood, PA
- General Electric, Global Research Ctr. Niskayuna, NY
- Toyota, Japan
- Mitsubishi, Japan
- …… others

Companies Producing SiC Power Transistors (6″ dia. Wafers)

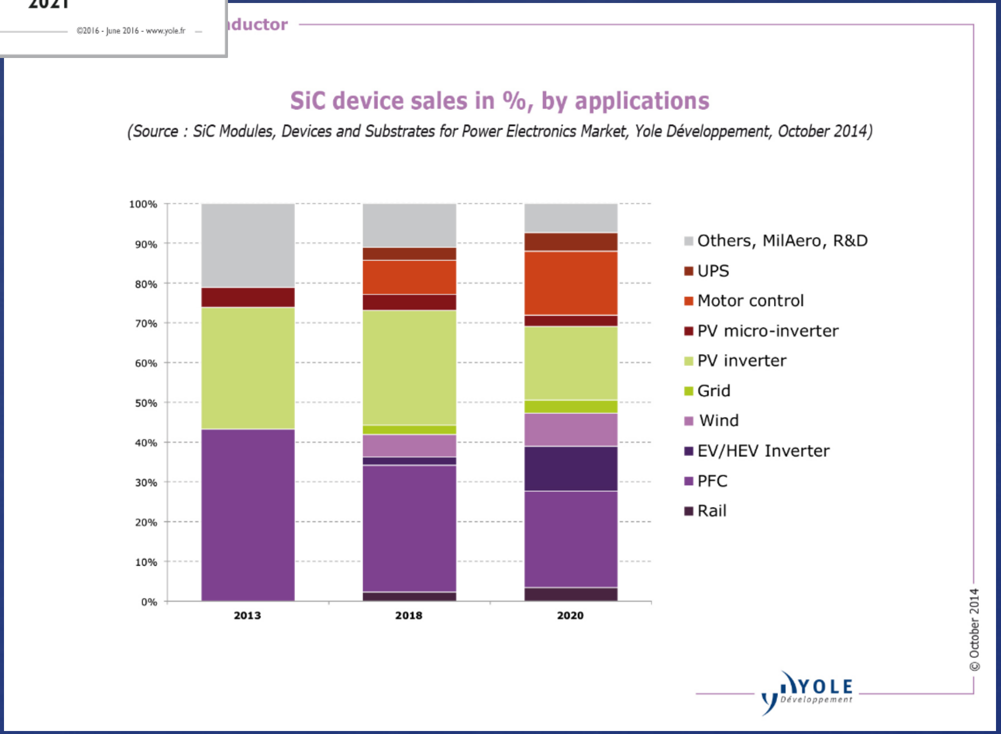




http://www.electronics-eetimes.com/news/sic-technology-soon-come-age

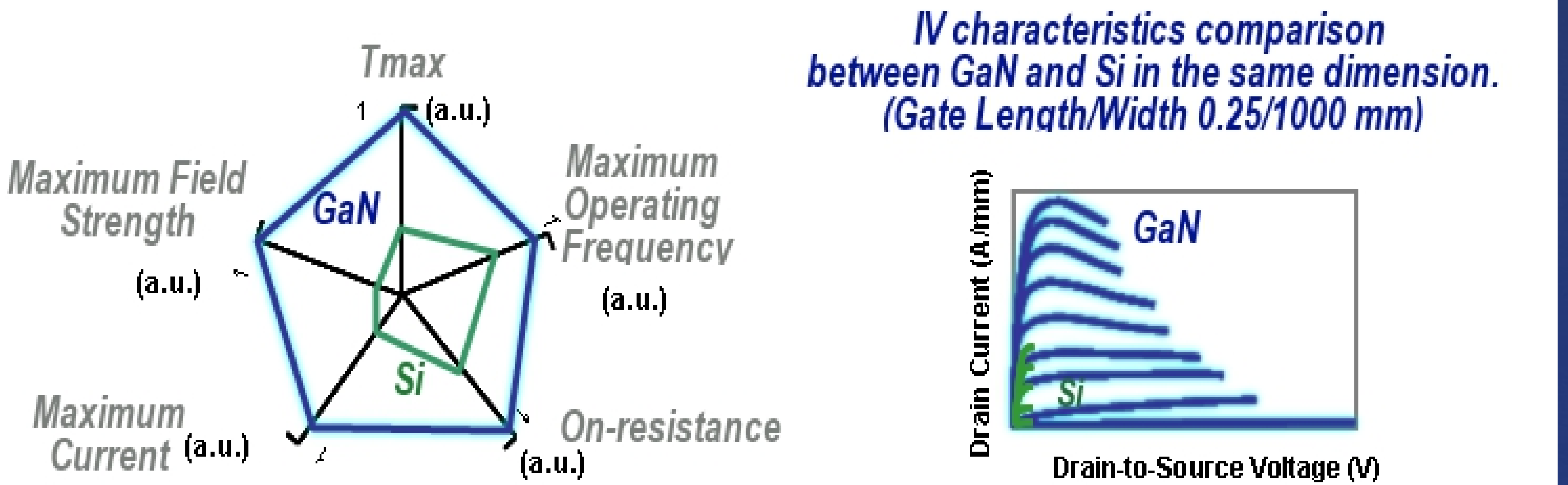


YOLE Développement
SiC device market (in M$)
(Source: Power SiC 2016: Materials, Devices, Modules, and Applications report, June 2016, Yole Développement)
600
400
200
0
2015
2016
2017
2018
2019
2020
2021
Transistor: 2015 - 2021 CAGR = 34%
Diode: 2015 - 2021 CAGR = 15%
©2016 - June 2016 - www.yole.fr



ductor
SiC device sales in %, by applications
(Source : SiC Modules, Devices and Substrates for Power Electronics Market, Yole Développement, October 2014)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2013
2018
2020
Others, MilAero, R&D
UPS
Motor control
PV micro-inverter
PV inverter
Grid
Wind
EV/HEV Inverter
PFC
Rail
© October 2014
YOLE Développement

Comparison of a Si MOSFET and a GaN HFET of the Same Dimsension



Ref: "Panasonic to Launch Industry's Smallest Enhancement-Mode 600V GaN Power Transistors, http://www.semicon.panasonic.co.jp/en/products/powerics/ganpower/

Today's transistors……Like MOSFET except High BV with High Current:

Furukawa Electric "High Power GaN HFETs on Si Substrates," pp. 17-23, Furukawa Review, No. 34, 2008.

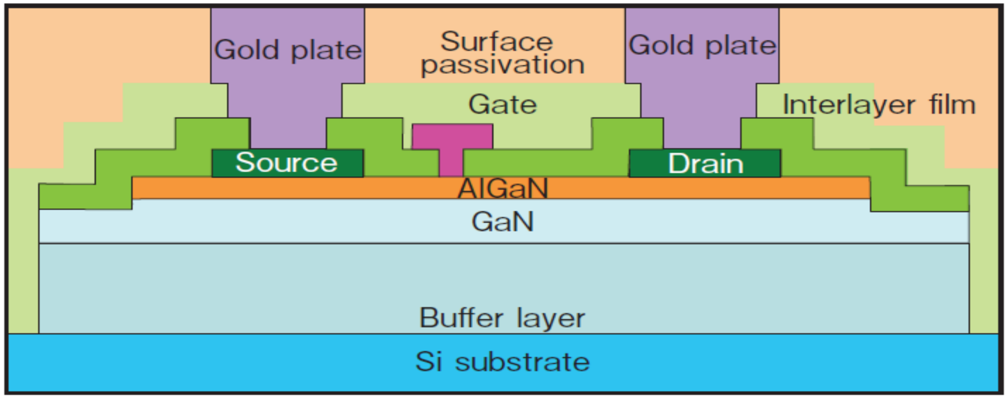
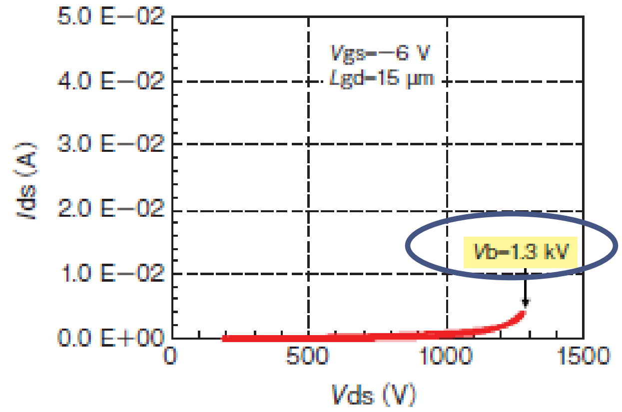
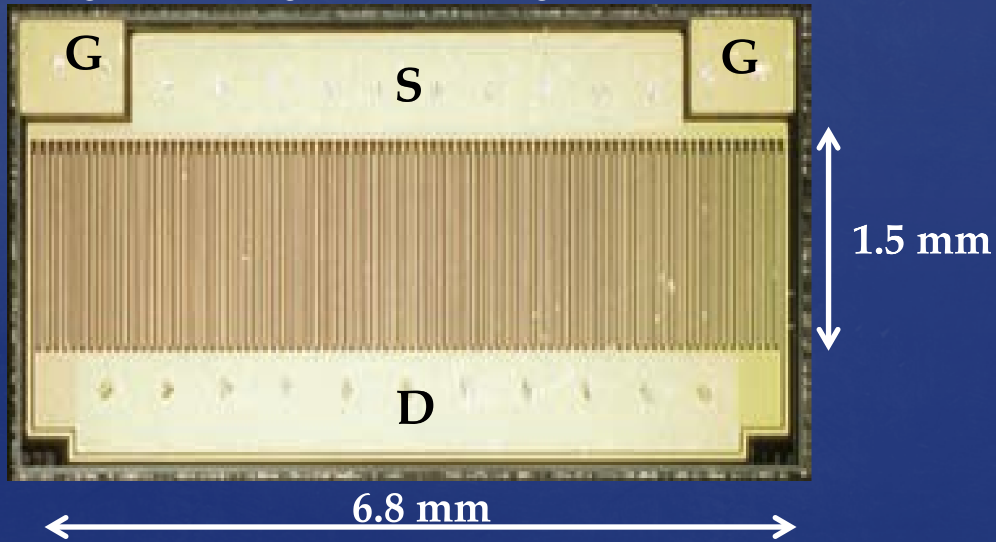


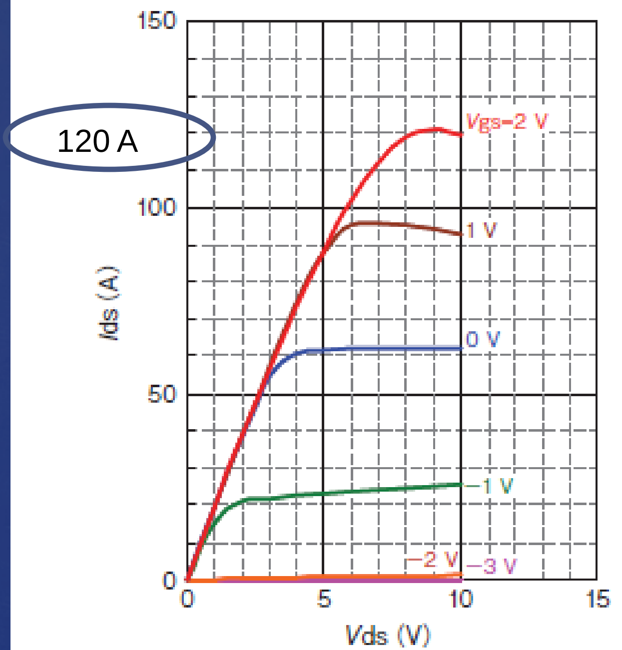
Figure 9 Schematic of HFET device structure on Si substrate.

Furukawa Review, No. 34 2008 19



L_g = 2 µm, L_{gd} = 15 µm, W_g = 340 mm





Companies Producing GaN Power Transistors

- Efficient Power Conversion Corp. (EPC), El Segundo, CA
- International Rectifier (now Infineon Technologies AG), El Segundo, CA
- Transphorm Inc., Goleta, CA
- RFMD, Greensboro, NC
- GaN Systems, Inc., Ottawa, Ontario, CANADA
- Panasonic Semiconductor Solutions Co., Nagaokakyo City, Kyoto, JAPAN
- VisIC Technologies, Ltd., Rehovot, ISRAEL
- Texas Instruments, Dallas, TX

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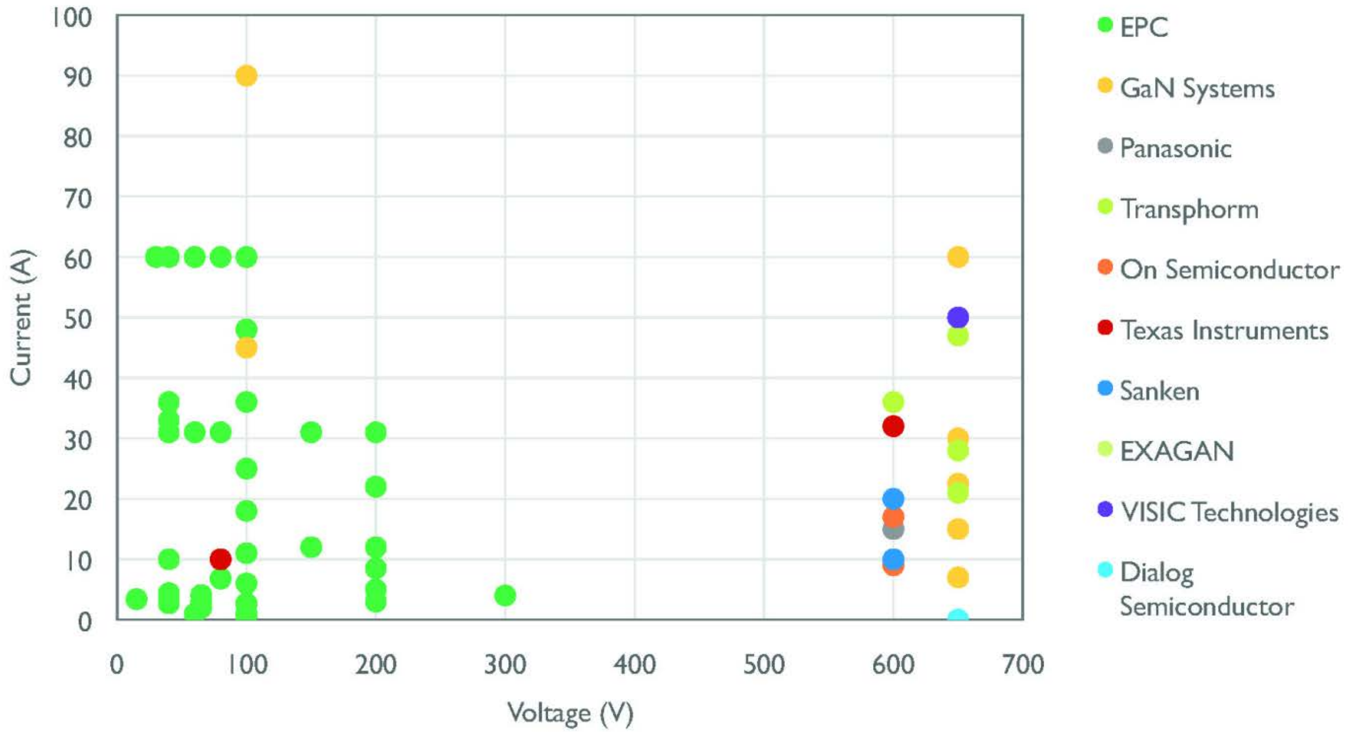
- Avogy, San Jose, CA

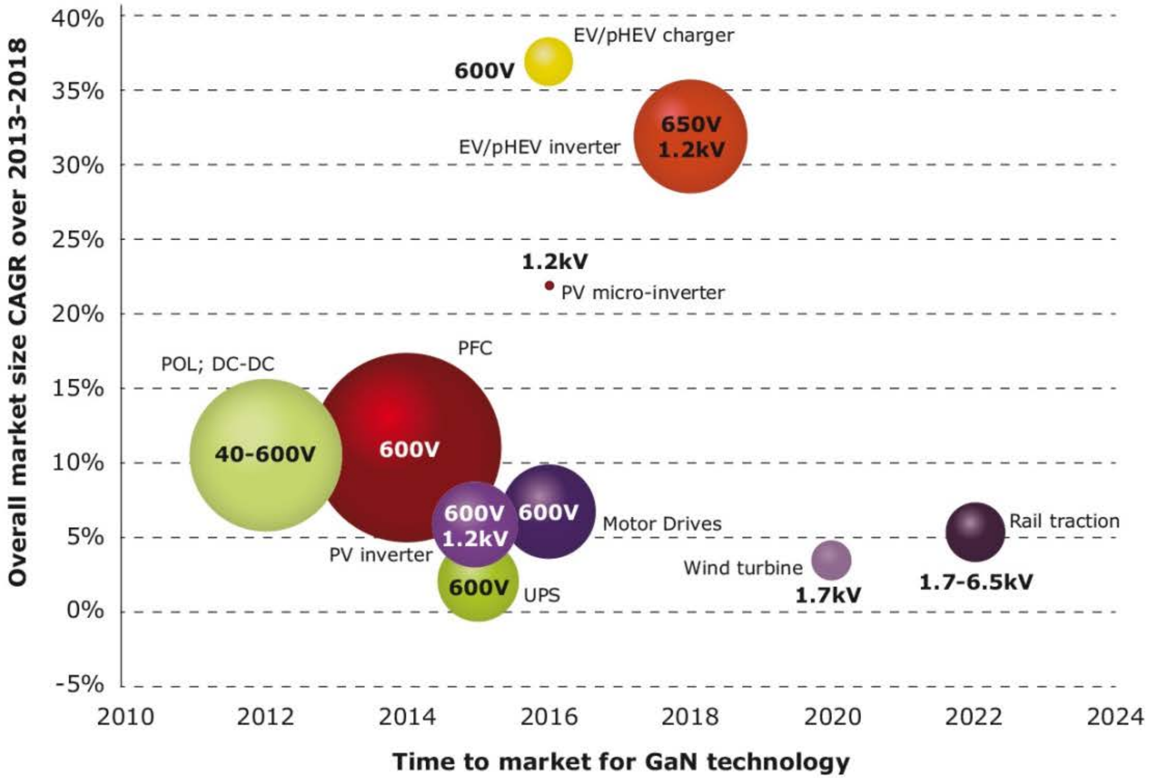
Existing GaN power devices

(Source: Power GaN 2016: Epitaxy and Devices, Applications, and Technology Trends 2016 report, September 2016, Yole Développement)



Estimated accessible markets, growth rate, and time-to-market for main GaN applications

(Source : Power GaN Market, Yole Développement, June 2014)



Keep a sharp lookout for exciting new research, development, and product offerings in WBGs and GaN, in particular, as well as new power electronic applications of these devices. New devices will open up more application opportunities.

China wide band-gap power semiconductor industry alliance

(Source : SiC Modules, Devices and Substrates for Power Electronics Market, Yole Développement, October 2014)

Wafer
- SICC
- TANKEBLUE 天科合达

Epi wafer
- TYSTC
- EpiWorld INTERNATIONAL

Device
- Global Power Technology Co., Ltd 泰科天润
- CETC 中国电子科技集团公司
- CorEnergy 科能芯
- Dynax 能讯半导体

Module and system
- State Grid Corporation of China 国家电网公司
- 嘉兴斯达半导体股份有限公司 STARPOWER SEMICONDUCTOR LTD.
- 河南森源 SENYUAN
- KEHUA TECH

中国南车 CSR 株洲南车时代电气股份有限公司 ZHUZHOU CSR TIMES ELECTRIC CO., LTD.

Today's Cutting Edge in GaN Power Transistors

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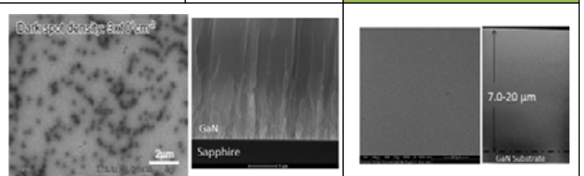
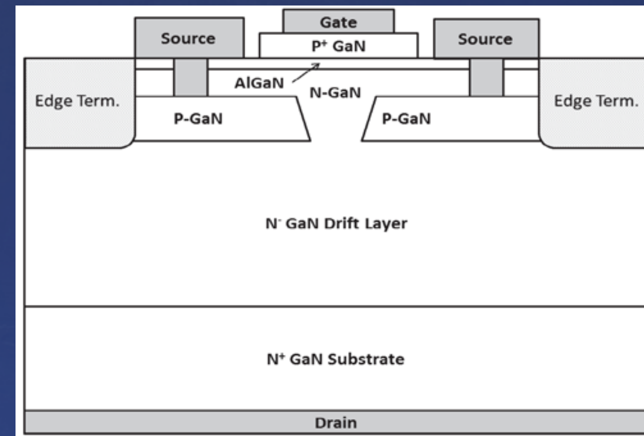
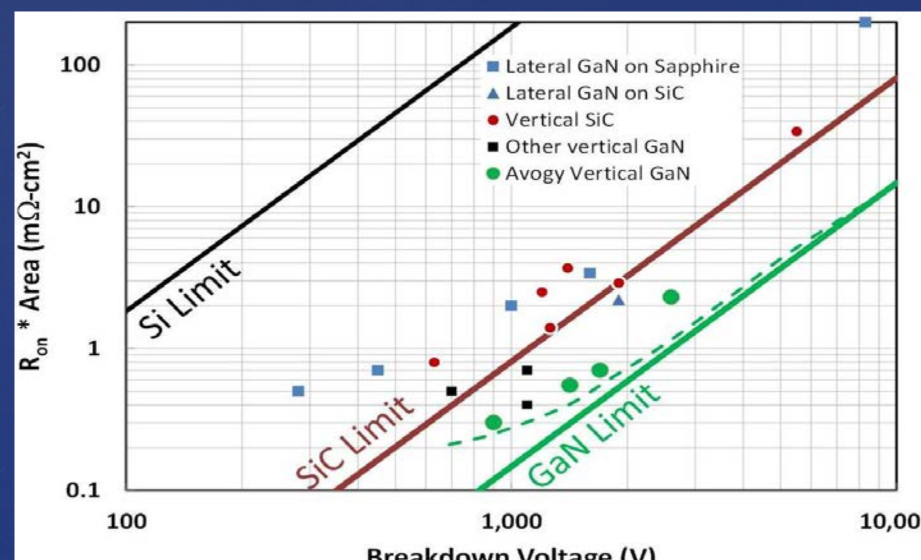
Avogy Corp: Vertical GaN grown by MOCVD on 2"-GaN substrates

Attributes	GaN on Si	GaN on SiC	GaN on Bulk-GaN
Defect Density (cm^{-2})	10^9	$5x10^8$	10^3 to 10^6
Lattice Mismatch, %	17	3.5	0
CTE Mismatch, %	54	25	0
Layer Thickness (µm)	< 5	< 10	> 50
Breakdown Voltage (V)	< 1000	< 2000	> 5000
Avalanche Capability	No	No	Yes
Device Types	Lateral	Lateral	Vertical and Lateral
Microscopy and Growth			





ref: I.C. Kizilyalli, P. Bui-Quanga, D. Disney, H. Bhatia, O. Aktas "Reliability studies of vertical GaN devices based on bulk GaN substrates," Microelectronics Reliability, MR-11704, 2015.

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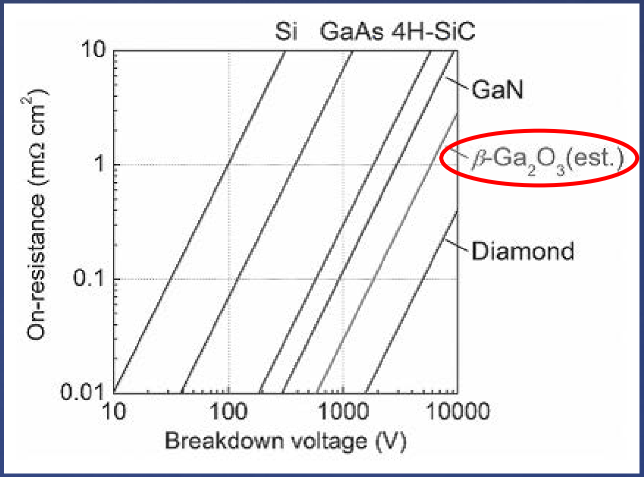
What Else?... Farther Out in Time… Gallium Oxide (β-Ga_2O_3)



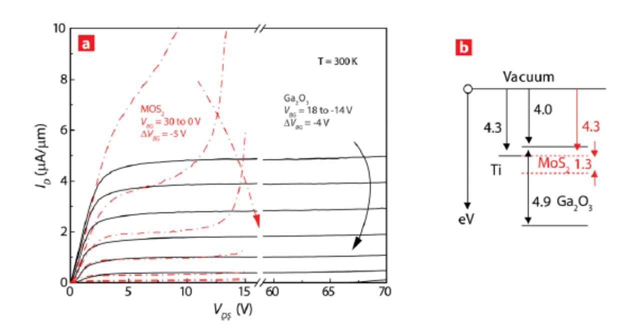
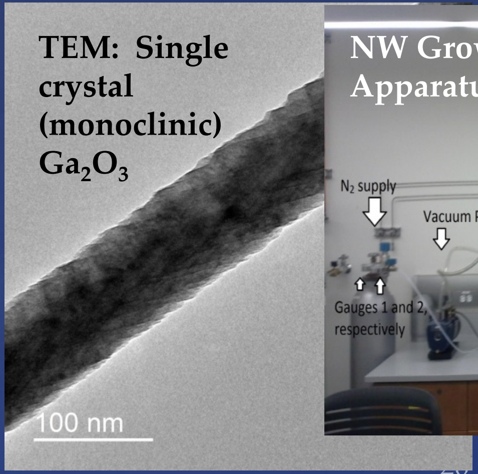
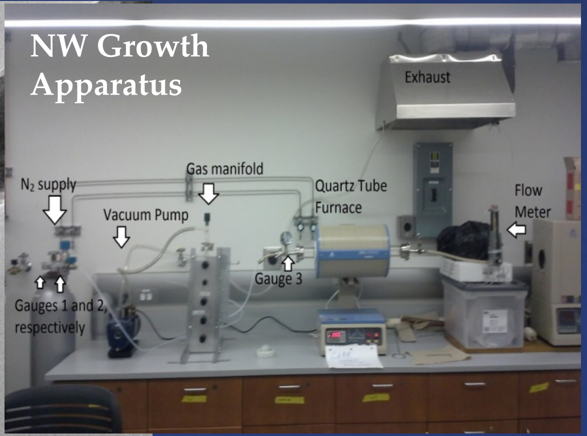


FIG. 6. (a) Common-source transistor characteristics, I_D vs. V_{DS} linear region and current saturation under high V_{DS}, and comparison of breakdown voltage of Ga_2O_3 with W/L = 1/3 μm and MoS_2 with W/L = 1/3 μm. (b) Band diagram of β-Ga_2O_3 comparing with MoS_2, indicating the formation of Schottky barrier contact between metal and β-Ga_2O_3.

W.S. Hwang, et al., "High Voltage Field-Effect Transistors with Wide-Bandgap bGa_2O_3 Nanomembranes," Appl. Phys. Lett., 104, 203111(2014).

Preliminary Research: Nano-Wires





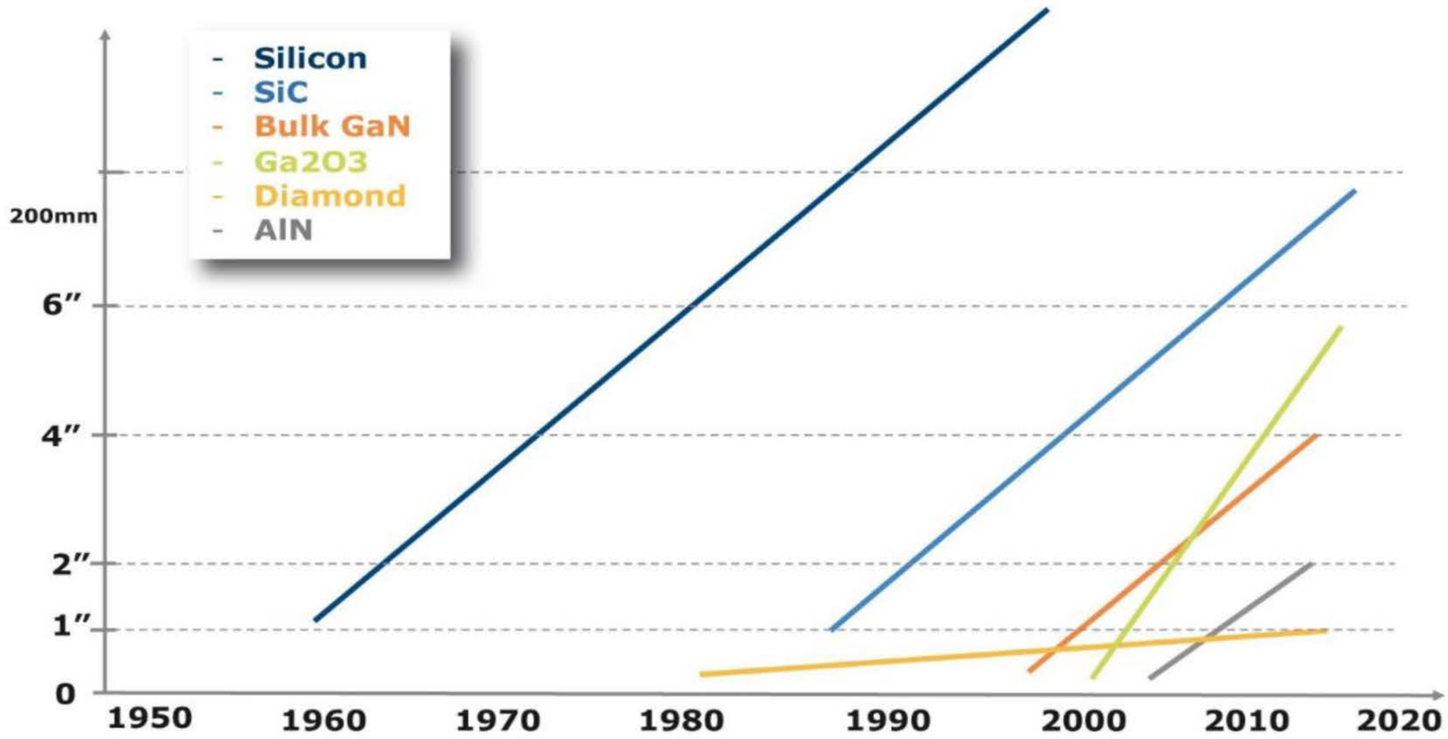
Advantages (Why?):

- High electron velocity (in micro-size GaN) at high electric fields: can this support fast devices at useful voltages in nano-size structures?
- Power device figure of merit (on-resistance vs. breakdown voltage) shows advantage of GaN and even further potential for Ga_2O_3
- Applications? → possible ultra-compact power switching devices and/or high dynamic range mixed-signal (interface) ICs to complement super-scaled CMOS or for monolithic control ckt.

DIFFERENT CRYSTAL DIAMETER EXPANSION

(Source: SiC, GaN and other WBG materials for power electronics applications report, *Oct. 2015, Yole Développement)*

SiC and GaN and other WBG materials represent new choices for power electronics applications.



YOLE Développement

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Conclusions

Wide Bandgap Semiconductors are a LEVERAGING TECHNOLOGY for Power Electronics Converters that offer potential advantages such as:

- Compact Size (and reduced weight)
- Higher Efficiency
- Improved Reliability

Market Trends and Predictions point to rapidly increasing adoption of WBGS technologies replacing Si.

SiC and GaN will be carving out their respective domains of benefit and application (including into harsh enviroments).

New technological advances will continue in these and other emerging WBGS.