Wide Bandgap Semiconductor Device Fundamentals and Applications

Lecture 1

WBG Semiconductor Devices

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Industrial Technology Research Institute
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Dr. Jih-Sheng (Jason) Lai
James S. Tucker Professor
Virginia Polytechnic Institute and State University
Future Energy Electronics Center
Blacksburg, VA 24061

Outline

- **Key properties of wide bandgap (WBG) semiconductors**
- **Why WBG devices?**
- **Application examples**
- **Potential issues and outlooks**

Bandgap Energy of Some Example Semiconductor Materials

Semiconductor	Bandgap Energy E_g (eV)
Tin	0.082
Germanium	0.66
Silicon germanium	1.10
Silicon	1.12
Indium Phosphide	1.35
Gallium arsenide	1.42
Cadmium selenide	1.70
Silicon carbide	3.26
Gallium nitride	3.49
Gallium oxide	4.50
Carbon (diamond)	5.47
Aluminum nitride	6.10
Boron nitride	7.50

- **Generally speaking, semiconductor materials have gone through three generations**
  - 1st Generation: silicon
  - 2nd Generation: gallium arsenide
  - 3rd Generation: silicon carbide, gallium nitride
- **Using silicon as the base line and as the 1st generation, all later generation materials refer to wide bandgap (WBG) semiconductors**
- **Silicon carbide (SiC) and gallium nitride (GaN) are the most prominent 3rd generation materials today**
- **Not all semiconductor materials are used for power electronics applications**

Key Properties of Wide Band Gap (WBG) Semiconductors

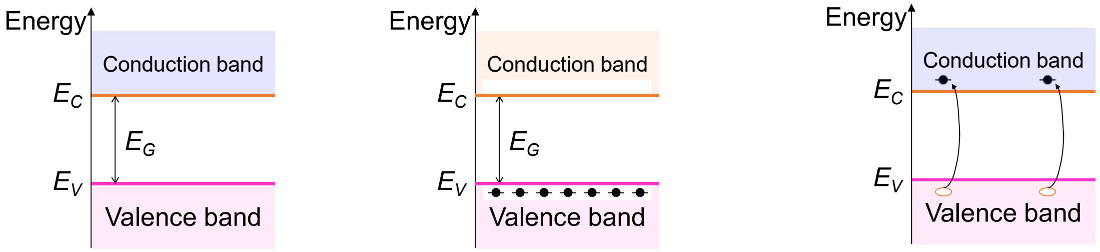
Material	A. **Band gap** (eV)	B. **Intrinsic carrier density** (/cm^3)	C. **Electron mobility** (cm^2/V·s)	D. **Saturation electron drift velocity** (10^7 cm/s)	E. **Breakdown electric field** (10^6·V/cm)	F. **Thermal conductivity** (W/cm°C)	Dielectric constant
Si	1.1	1×10^{10}	1500	1.0	0.3	1.3	11.8
SiC-4H	**3.26**	**8.2×10^{-9}**	650	**2.0**	**3.0**	**4.9**	10.0
GaN	**3.4**	**1.9×10^{-10}**	2000	**2.5**	**3.3**	1.3	9.5
β-Ga_2O_3	**4.5-4.9**	**1.79×10^{-23}**	100-300	10	**>5.0**	**0.11-0.27**	11.9
Diamond	**5.45**	**1×10^{-27}**	1900	**2.7**	**5.6**	20	5.5
AlN	**6.1**	**1×10^{-31}**	1100	**1.8**	**11.7**	2.5	8.7

- There are many reasons that show WBG semiconductor materials are superior to silicon, with the above A, B, C, D, E, F factors explained in the following pages.
- Quite a few nitride materials: AlN, InN, AlGaN, AlInN, etc. are all promising for optoelectronic devices and high power high temperature electronics

Source:
1. F. Ren and J.C. Zolper, *Wide Energy Bandgap Electronic Devices*, World Scientific, 2003
2. T. Igawa, "Unleashing the Potential of α-Ga_2O_3," IEEE CMPT Symposium, Japan, 2019
3. M. Higashiwaki and G.H. Jessen, "The Dawn of Gallium Oxide Microelectronics," Applied Physics Letter, #112, 2018

A. What is Bandgap?

- Bandgap (E_G) is the minimum "energy" needed to break a covalent bond in the semiconductor crystal, and thus freeing electrons for conduction. E_G is typically represented in electronic-volt (eV).
- Consider the lowest energy level at conduction band, E_C, and the highest energy level at valence band E_V. Bandgap energy is defined as $E_G \equiv E_C - E_V$



(a) Basic energy band model

(b) At 0°K, valence band filled with electrons; conduction band is in empty state. No current flow when applying electric field because there are no free electrons in conduction band, no holes in filled valance band to support current flow.

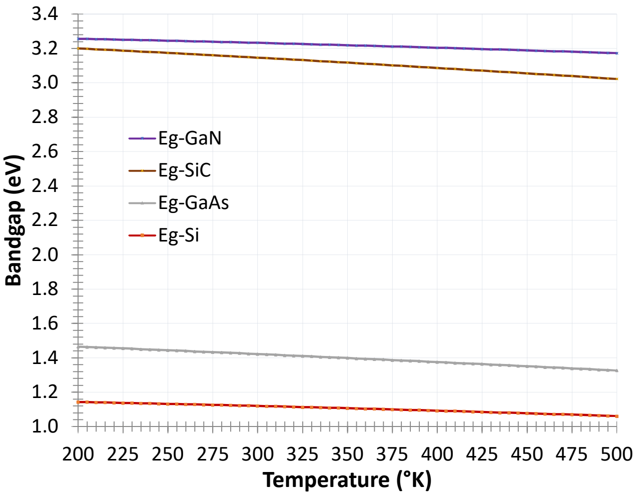
(c) At > 0°K, creation of electron-hole pair by thermal excitation across the energy bandgap. A few electrons gain the energy to jump from valance to conduction band. Covalent bond is broken. The "density of these free electrons" is "**intrinsic carrier density**"

Bandgap as a Function of Temperature

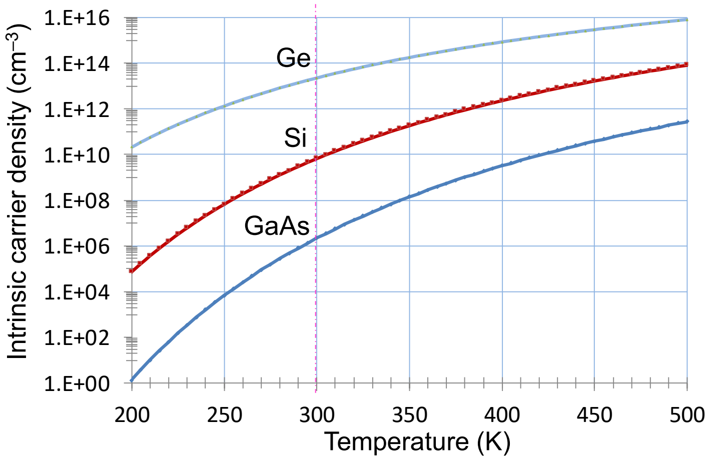
- Bandgap decreases as temperature increases
- Coefficients are obtained from empirical data
- Increase of doping density can decrease the bandgap, which is also material dependent

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

E_g (eV)	T = 0°K	α	β
Si	1.1660	4.73E-04	636
GaAs	1.5190	5.41E-04	204
4H-SiC	3.2600	7.70E-04	311
GaN	3.2800	4.73E-04	600



B. Intrinsic Carrier Density



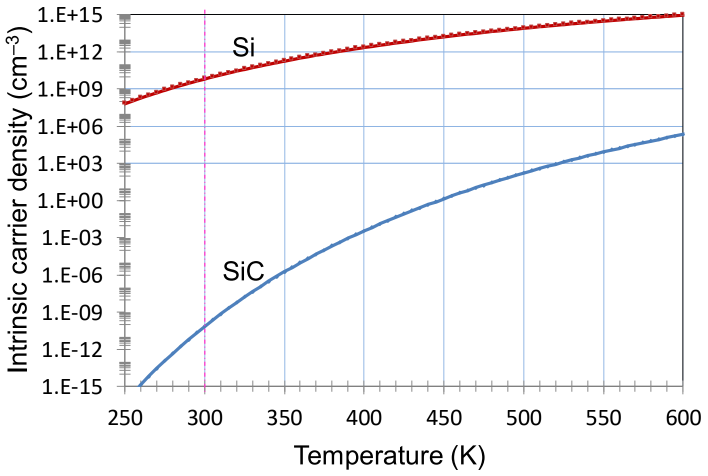
$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right)$$

- E_G = semiconductor bandgap energy in eV
- k = Boltzmann's constant, 8.62 x 10^{-5} eV/K
- T = absolute temperature, °K
- B = material-dependent parameter,

	B ($K^{-3}cm^{-6}$)	E_G (eV)
Ge	2.31×10^{30}	0.66
Si	1.08×10^{31}	1.12
GaAs	1.27×10^{29}	1.42

- Intrinsic carrier density is often denoted as n_i with a unit of electrons/cm^3.
- Wider bandgap (E_G), lower n_i.
- Higher temperature, higher n_i.

Intrinsic Carrier Density Comparison Between Si and SiC



- WBG materials have n_i several orders of magnitude lower than that of Si material
- Lower n_i tends to allow higher doping concentration, and
- Doping concentration of donors (e.g. P) and acceptors (e.g. B) will determine the conductivity

Source: B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer, 2008.

Electron and Hole Densities

- “**Electron density**” is denoted as n with a unit of electrons/cm^3.
- Electron has a charge $-q$ equal to -1.602×10^{-19}
- When one electron is moved away from the covalence bond, the vacancy is left with an effective charge of $+q$, which is called “hole”
- “**Hole density**” is denoted by p with a unit of holes/cm^3
- For intrinsic semiconductor, $n = p = n_i$, and the product of electron and hole concentrations is

$$pn = n_i^2$$

- This pn product is given when a semiconductor is in “thermal equilibrium.” Material properties are dependent only on the temperature.

C. Mobility

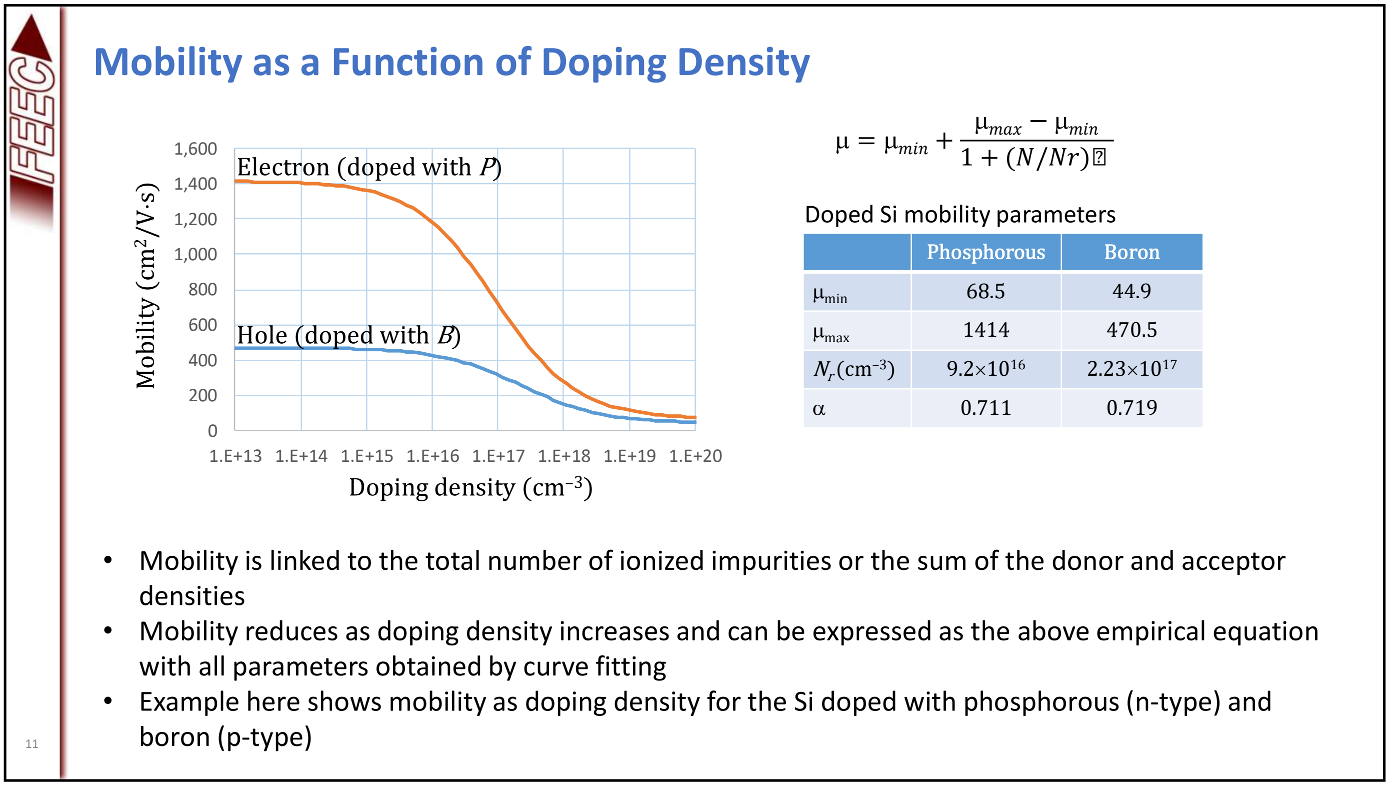
- Electron (or negative charge) moves or drifts with negative electric field. The drift velocity v_n (cm/s) is proportional to electric field E (V/cm) and “**electron mobility**” μ_n.

$$v_n = -\mu_n E$$

- Hole (or positive charge) drifts with positive electric field, and its velocity v_p (cm/s) is proportional to electric field E (V/cm) and “**hole mobility**” μ_p.

$$v_p = \mu_p E$$

- In intrinsic silicon, μ_n = 1350 cm^2/V·s, and μ_p = 500 cm^2/V·s
- Hole moves only through covalent bond broken, but electron moves freely, and thus in a much faster speed.



Mobility as a Function of Doping Density

$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + (N/Nr)^{\alpha}}$$

Doped Si mobility parameters

	Phosphorous	Boron
μ_{min}	68.5	44.9
μ_{max}	1414	470.5
N_r(cm^{-3})	9.2×10^{16}	2.23×10^{17}
α	0.711	0.719

- Mobility is linked to the total number of ionized impurities or the sum of the donor and acceptor densities
- Mobility reduces as doping density increases and can be expressed as the above empirical equation with all parameters obtained by curve fitting
- Example here shows mobility as doping density for the Si doped with phosphorous (n-type) and boron (p-type)

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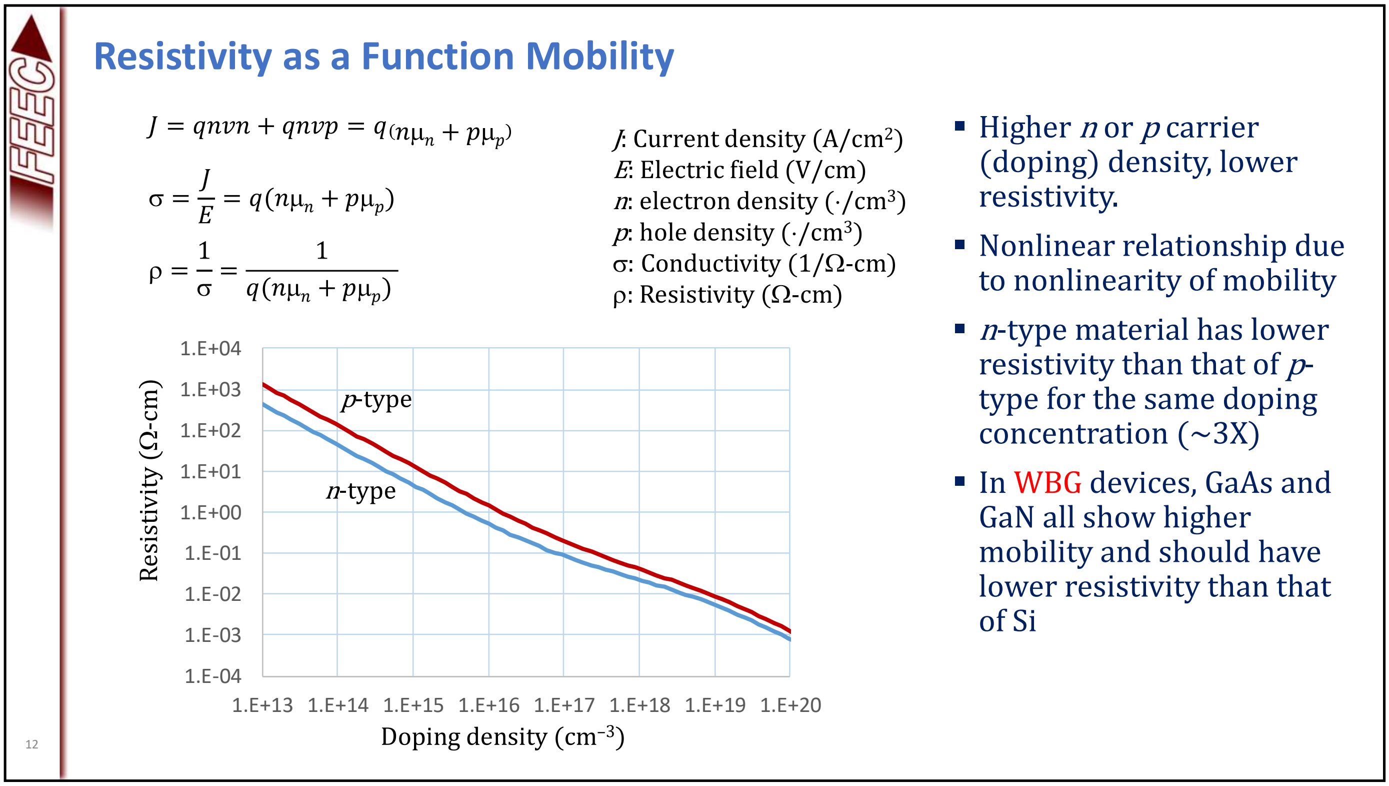

Resistivity as a Function Mobility

$$J = qnvn + qnvp = q(n\mu_n + p\mu_p)$$

$$\sigma = \frac{J}{E} = q(n\mu_n + p\mu_p)$$

$$\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)}$$

J: Current density (A/cm²)
E: Electric field (V/cm)
n: electron density (·/cm³)
p: hole density (·/cm³)
σ: Conductivity (1/Ω-cm)
ρ: Resistivity (Ω-cm)

- Higher *n* or *p* carrier (doping) density, lower resistivity.
- Nonlinear relationship due to nonlinearity of mobility
- *n*-type material has lower resistivity than that of *p*-type for the same doping concentration (~3X)
- In WBG devices, GaAs and GaN all show higher mobility and should have lower resistivity than that of Si

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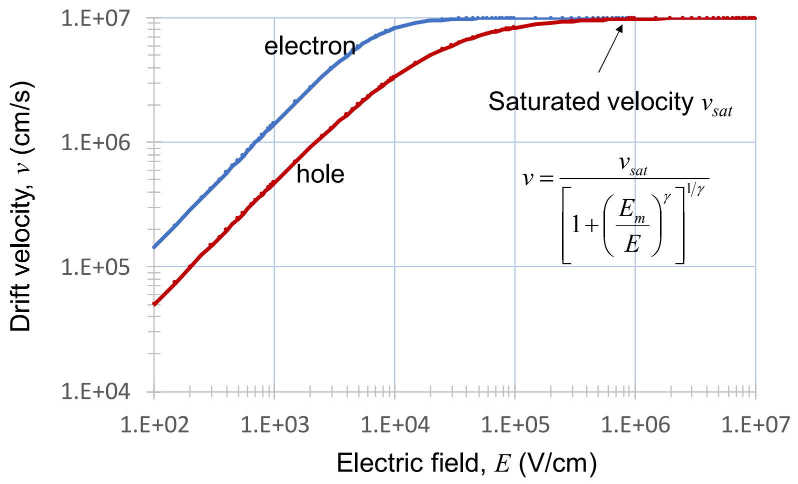
D. Velocity Saturation

- Velocity of any carrier (electron or hole) cannot exceed speed of light
- Given an electric field, the velocity saturates at a limit, or the "**Saturated Drift Velocity**" v_{sat}.
- For silicon, v_{sat} is approximately 10^7 cm/s.
- Drift velocity is nonlinear when approaching the saturation but is quite linear when electric field is low.
- Example: Given E = 1 kV/cm, v_n = 1350·1000 = $1.35 \cdot 10^6$ cm/s, which is below saturation region; With E > 3 kV/cm, electron velocity is no longer linear and saturates at 10^7 cm/s when E = 30 kV/cm.
- WBG semiconductors tend to have higher v_{sat} and thus allowing higher **electric field** for the same velocity.

Silicon Carrier Drift Velocity



$$v = \frac{v_{sat}}{\left[1 + \left(\frac{E_m}{E}\right)^{\gamma}\right]^{1/\gamma}}$$

For silicon:
$v_{sat} \cong 10^7$ cm/s

For electrons:
$E_m = 7 \cdot 10^3$ V/cm
$\gamma = 2$

For holes:
$E_m = 2 \cdot 10^4$ V/cm
$\gamma = 1$

S. Linder, *Power Semiconductor*, EPFL Press distributed by CRC Press, 2006
D.M. Caughey and E.E. Thomas, "Carrier Mobilities in Silicon Empirically Related to Doping and Field," Proc. IEEE, 55, 2192, 1967.

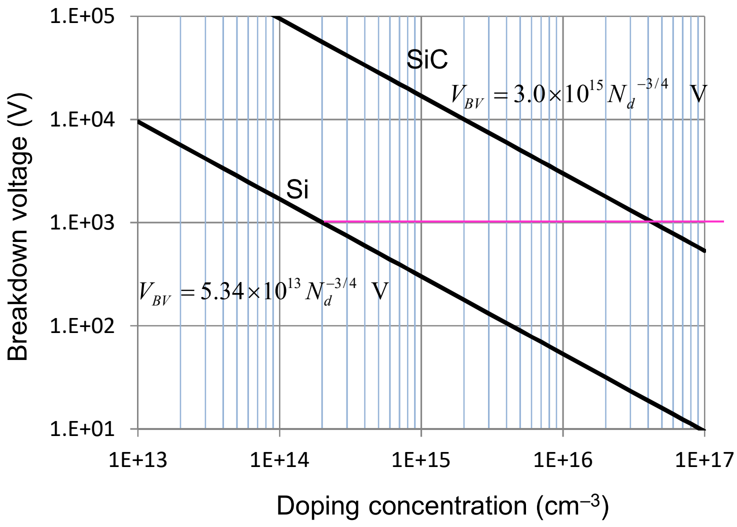
Semiconductor Conductivity

- Electrical conductivity σ in semiconductor is associated with electron and hole flow (or drift) current density and thus the electron and hole concentrations, n and p.

$$\sigma = q(n\mu_n + p\mu_p)$$

- For n-type semiconductor, $n \cong N_d$ = the donor doping concentration with $N_d >> n_i$
- For p-type semiconductor, $p \cong N_a$ = acceptor doping concentration $N_a >> n_i$
- In other words, **higher doping concentration, higher conductivity, or lower resistivity**
- However, next page will show that **higher doping concentration, lower breakdown voltage level ➔** one of the main reasons that we need WBG devices

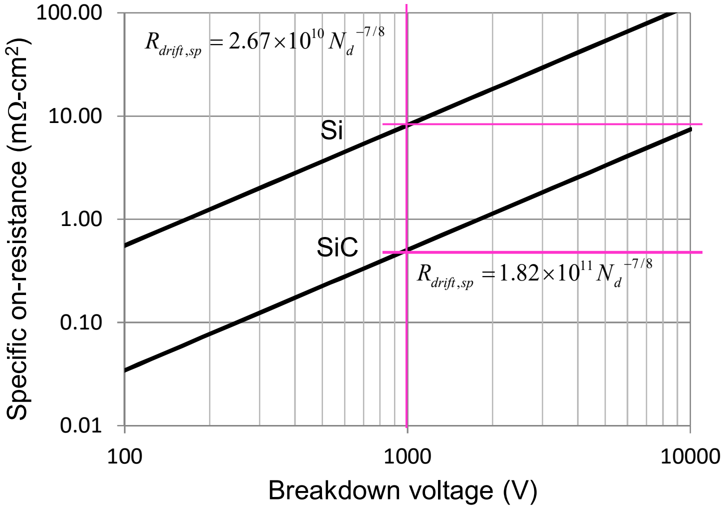
E. Breakdown Voltage Comparison for Si and 4H-SiC Devices at Different Doping Levels



At 1 kV,
N_d =
2.01×10^{14} for Si
4.32×10^{16} for SiC (This reflects more free electrons, 200X)

Source: B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer, 2008.

Comparison of Drift Region Specific On-Resistance



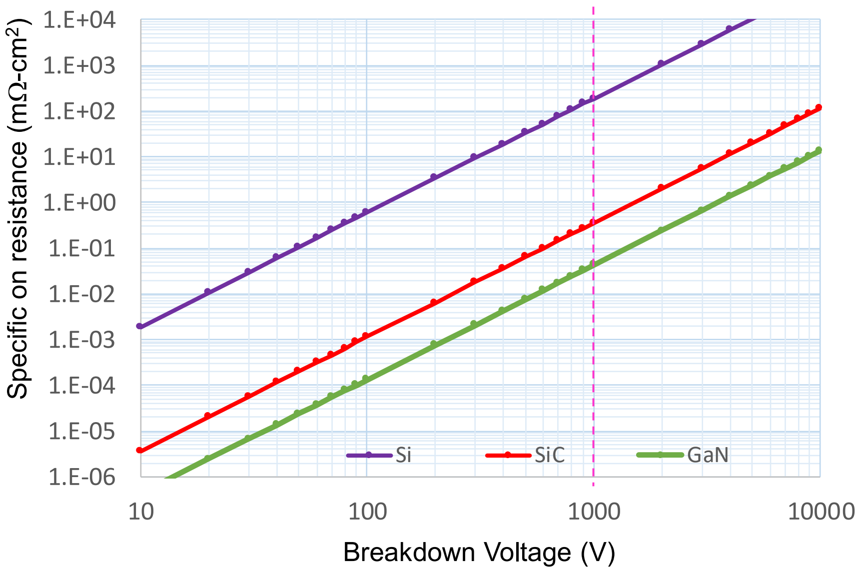
- **At 1 kV, drift region specific on-resistance $R_{drift,sp}$ =**

  8.15 mΩ-cm² for Si
  0.74 mΩ-cm² for SiC

- **Potentially SiC can reduce the chip area by >10X, which translates to C_{oss} or switching loss reduction**
- **Smaller chip size also refers to cost reduction**

Source: B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer, 2008.

Drift Region $R_{on,sp}$ Comparison Between Si, SiC, and GaN Devices



For silicon,

$$R_{on,sp} = 5.93\cdot10^{-9}\cdot V_{BV}^{2.5}$$

For SiC,

$$R_{on,sp} = 1.13\cdot10^{-11}\cdot V_{BV}^{2.5}$$

For GaN,

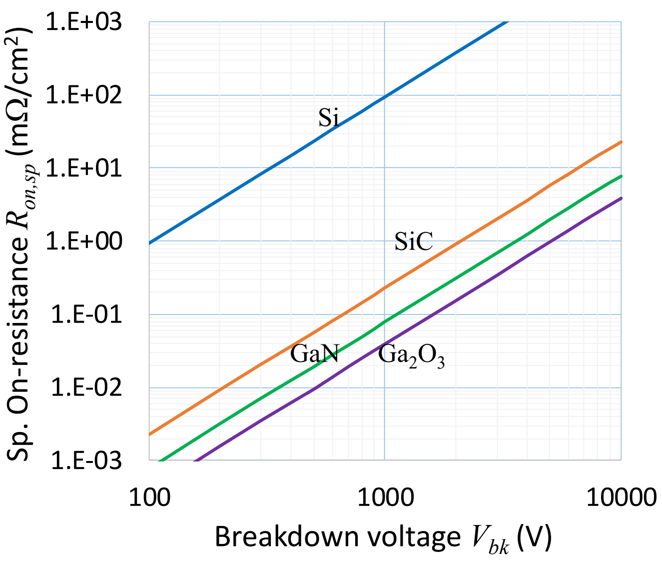
$$R_{on,sp} = 3.25\cdot10^{-12}\cdot V_{BV}^{2.5}$$

Power Figure of Merit (FOM) is a Function of Breakdown Voltage

$$\text{BFOM} = \varepsilon \cdot \mu \cdot E_C^3$$

$$\boxed{R_{on,sp} = \frac{4V_{bk}^{2}}{\varepsilon \cdot \mu \cdot E_C^{3}}} \leftarrow \text{BFOM}$$

- For a given breakdown voltage V_{bk}, lower on-drop resistance, better figure of merit (FOM)
- Without considering switching losses, power FOM can be compared with $R_{on,sp}$
- All WBG devices are showing orders of magnitude better than the Si device



F. Thermal Conductivity

- **For high-power applications, removing the heat away is critical for high-density designs.**
- **SiC exhibits superior thermal conductivity (4.9 W/cm°C) that puts it a candidate for high-power high density applications such as traction motor drives.**
- **Extremely low thermal conductivity (0.11-0.27 W/cm°C) of GaN makes it difficult for ultrahigh power density applications. The only viable solution is to design ultrahigh efficiency power conversions, which reduces the heat production substantially.**
- **Both SiC and GaN are much more efficient devices with small chip size while providing high current carrying capability. This small chip size actually creates some concerns about**
  - **Short ckt capability, which can occur due to noise triggering or PWM signals mixed up by unknown reasons**
  - **Avalanche capability, which can occur due to parasitic inductance and fast devie turn-off induced false triggering**
- **To adopt GaN in high-power circuits is much more challenging due to its low thermal conductivity and much faster speed.**

Summary of WBG Device Properties

- WBG semiconductor devices demonstrate superior features on
    - chip size reduction,
    - fast switching speed,
    - low conduction voltage drop,
    - high voltage blocking capability
- Compared to Si devices, WBG devices are considered ideal devices as key performance indexes are orders of magnitude better than that of Si devices
- The thermal conductivity feature is mixed as SiC is showing a much higher thermal conductivity, GaN is actually showing a much lower thermal conductivity
- With fast switching turn-on and turn-off speeds, dv/dt and di/dt slew rates are much higher, which coupling with the smaller chip size substantially reduce the short circuit and avalanche capabilities that some industries strongly desire to have for safety and reliability concerns.

Outline

- Key properties of wide bandgap (WBG) semiconductors
- **Why WBG devices?**
- Application examples
- Potential issues and outlooks

Why WBG Semiconductor Devices?

Specific on-resistance (mΩ-cm²) for the conducting (drift) region can be expressed as:

$$R_{on,sp} = \frac{W_d}{q\mu_n N_d}$$

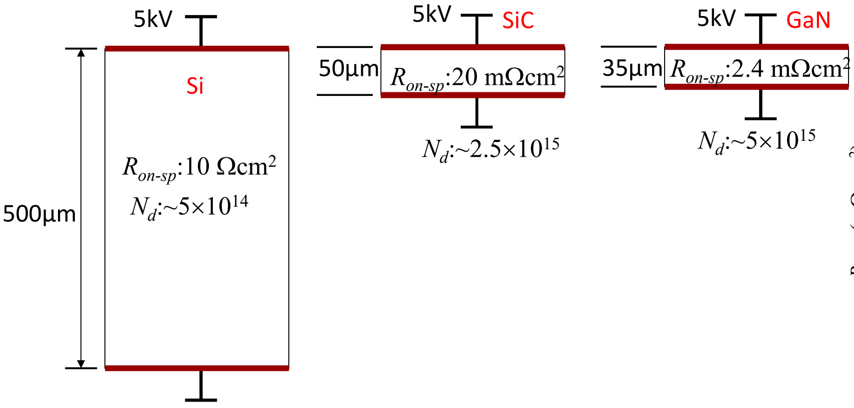
W_d = drift region width, a function of given V_{BV}
N_d = doping density, a function of given V_{BV}
V_{BV} = breakdown voltage (V)
μ_n = mobility (cm²/V·s)
$q = 1.6\times10^{-19}$

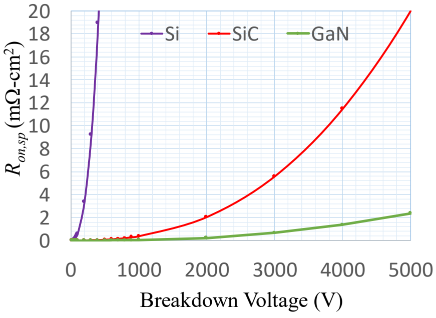
For SiC $W_d = 2.33\times10^{-7} V_{BV}^{7/6}$
For GaN $W_d = 1.7\times10^{-7} V_{BV}^{7/6}$
For SiC $N_d = \frac{1.98\times10^{20}}{V_{BV}^{4/3}}$
For GaN $N_d = \frac{3.98\times10^{20}}{V_{BV}^{4/3}}$

- Mobility (μ_n) – Base line Si (1500)
  - most favorable: GaAs (3000), then GaN (2000), least favorable: SiC (650)
- Critical breakdown voltage field – Baseline Si (0.3)
  - AlN (11.7) the most favorable, then Diamond (5.6), GaN (3.3), SiC (3.0)
- Overall, higher breakdown voltage is more favorable for low on-drop resistance. Therefore, using ($\varepsilon \mu_n E_c^3$) as the figure of merit (FOM), the wide bandgap semiconductor choice sequence becomes AlN → Diamond → GaN → SiC → GaAs

Source: B. J. Baliga, *Gallium Nitride and Silicon Carbide Power Devices*, World Scientific, Singapore, 2017.

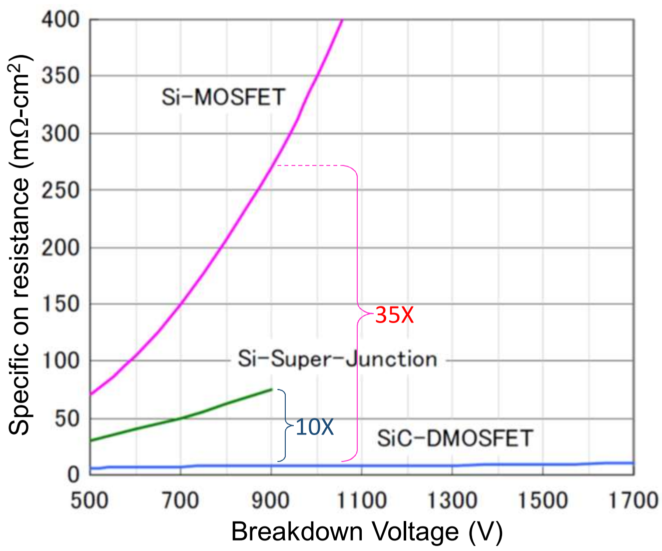
Drift Region Dimension Comparison Between Si, SiC, and GaN Devices at 5kV





- **Using 5 kV breakdown voltage as example for channel width comparison, SiC shows 10X reduction, and GaN shows 14X reduction**
- **For specific on-drop resistance comparison at 5 kV, SiC shows 500X reduction, and GaN shows 4000X reduction**
- **Note that such an on-drop resistance reduction depends on the voltage level. Higher voltage, more saving. This can be easily understood in the non-exponential scale**

Commercial Si and SiC Products $R_{on,sp}$ Comparison

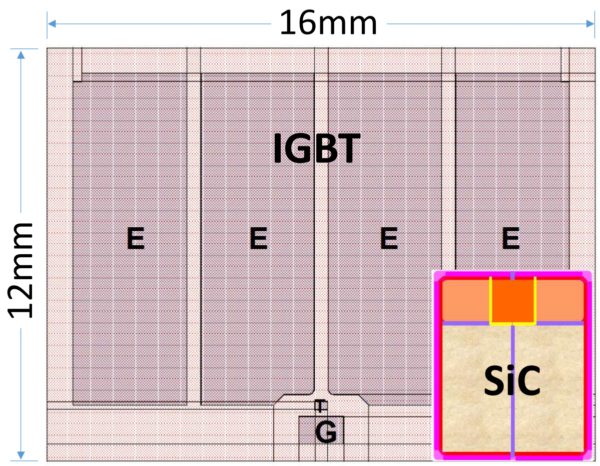


- Highest SJ-junction MOSFET voltage available today is 900 V, thus only 900 V level is compared
- Based on existing commercial products, SiC MOSFET reduces $R_{on,sp}$ by 35 times as compared to Si MOSFET and 10 times as compared to super-junction Si MOSFET
- Extended curve indicates more reduction with SiC at higher voltages

ROHM "SiC Power Devices and Modules – Application Notes," June 2013

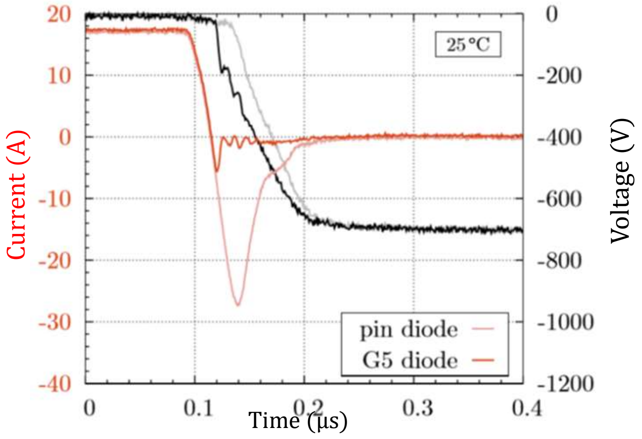
Die Size Comparison 1200-V Si IGBT vs. SiC MOSFET

Why SiC?



- Power Density
  - Si IGBT (matured): 1 A/mm^2
  - SiC MOSFET (3rd gen): 5 A/mm^2
- Wafer Cost
  - Si: ≈ $20/6"
  - SiC: ≈ $1500/6" (75X)
- Cost Power Ratio (assume the same yield): 15
- Number doesn't look attractive today, but why SiC?

SiC MOSFET Body Diode Reverse Recovery Characteristic



- **SiC MOSFET Body Diode Reverse Recovery Characteristic is Comparable to that of Merged PiN-Schottky (MPS) Diodes**
- **As compared to IGBT, diodes and related packaging are additional saving in inverter applications**
- **There is no need for SiC MOSFET to add an anti-paralleled Schottky or MPS diode – additional cost saving**

Cost Performance Index Comparison – Big Justification Reason

A. ST Micro estimate (supplier of Tesla)

Device (1200 V rated)	Si IGBT + Diode	SiC MOSFET	Value proposition
Die area for 100A/mm²	170	35	5X chip area reduction
Normalized power losses	3-5	1.0	60% loss/heat sink reduction 2-9% mileage extension
Junction temp at nominal power (°C)	100	90	Life expectancy extended
Maximum junction temp (°C)	175	200	

B. Cree/Wolfspeed estimate (supplier of Lucid Air)

BOM cost saving	Per vehicle basis
Battery cost	\$320-\$640
Space saving	\$600
Cooling cost reduction	\$500 to \$1000

More than enough to justify 15X SiC chip cost

Sources:
1. Vittorio Giuffrida, Simone Buonomo, Anselmo Gianluca Liberti, "Silicon Carbide Enabling Car Electrification," APEC-2019 Industry Session 020-1039
2. Guy Moxey, Silicon Carbide: Transforming the Future of Power, https://www.wolfspeed.com/knowledge-center/article/silicon-carbide-transforming-the-future-of-power/, Jun 26, 2019

Outline

- Key properties of wide bandgap (WBG) semiconductors
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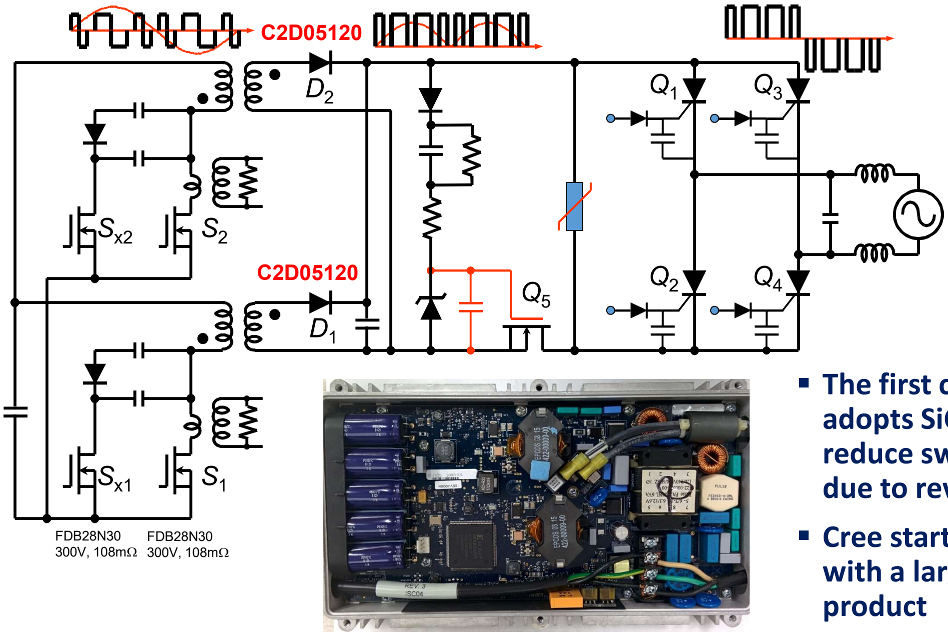
First Commercial Product Adopting SiC Diodes – PV Microinverter

First Tipping Point of SiC Commercialization



Enphase M250:
Interleaved flyback + unfolding single-stage inverter

- **The first commercial product that adopts SiC diodes, D_1 and D_2 to reduce switching losses that are due to reverse recovery**
- **Cree started 6” wafer production with a large demand of this PV product**

First Commercial Product Adopting GaN HEMT – USB 3 Type C Chargers

- By adopting GaN device for laptop PC/Mobile Phone universal charger, size and weight reduction is ~10X ➔ Much higher efficiency and portability
- Consider GaN is in its infant stage, but Si is mature (>60 year old). Future with GaN for DC powered system is unimaginable

Laptop PC charger today: 600 g

GaN device based universal charger, size: smaller than a business card, 56 g

Example Commercial Chargers Powered by Navitas GaNFast™

amazon

68W

ANKER

120W

AUKEY

100W

chargeasap

200W

DELL

90W

Lenovo

65W

RAVPOWER

65W

realme

150W

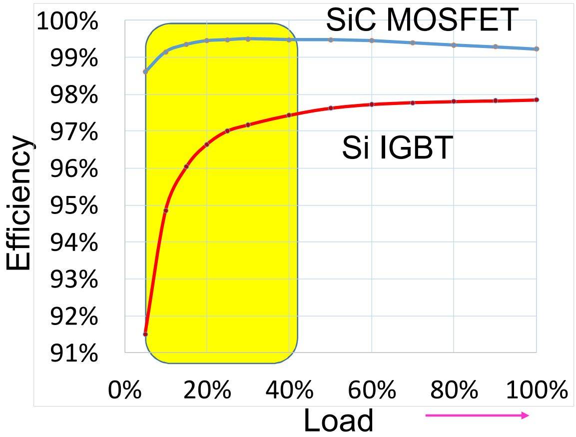
SlimQ

240W

SAMSUNG

45W

First Commercial Product Adopting SiC MOSFETs



- The first commercial product adopting SiC MOSFET for EV traction inverter with significant motor drive efficiency improvement.
- Especially at light loads, the loss is reduced by >80% ➔ a big gain on urban driving cycle

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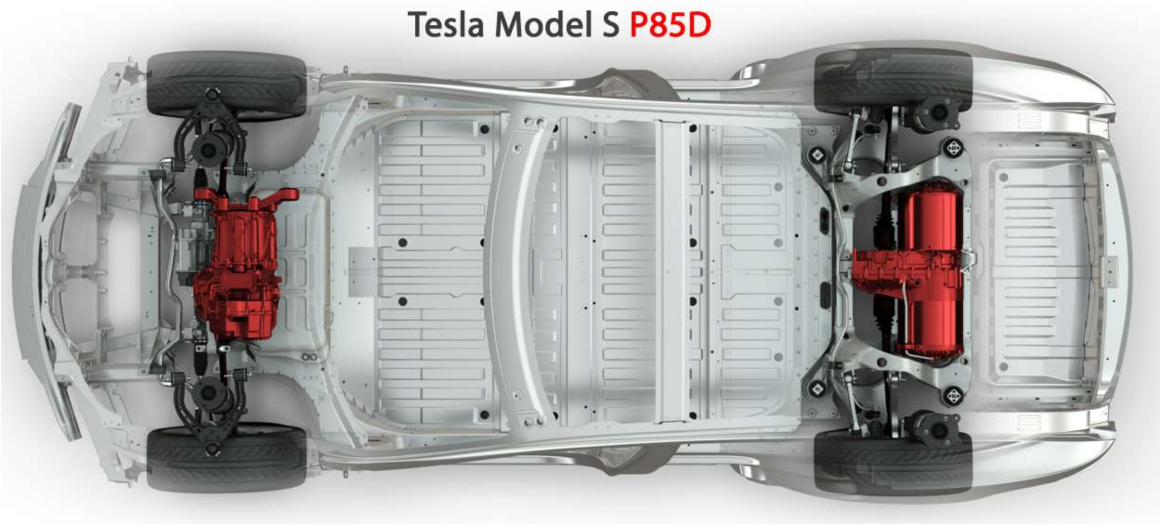
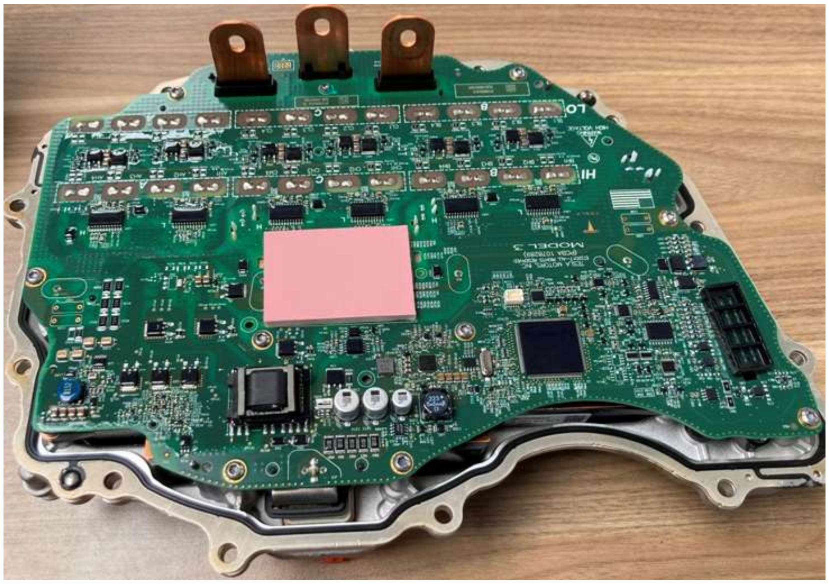
There are Multiple Traction Motor Drives in a Typical EV



- Car companies make it optional to have front-wheel or all-wheel drives
- For rear-wheel drivetrain, there is also an option of one or two motors
- Up to three motors in this specific EV model

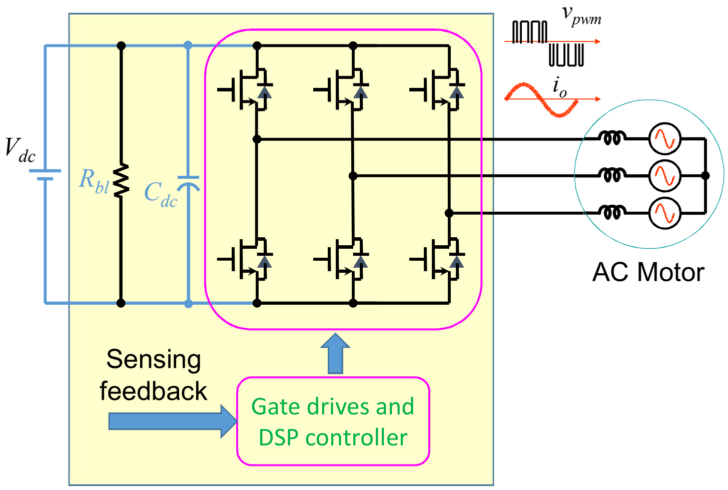
Inverter Shape Fits Front and Rear Motors



Tesla Model 3 - Front

Tesla Model 3 - Back

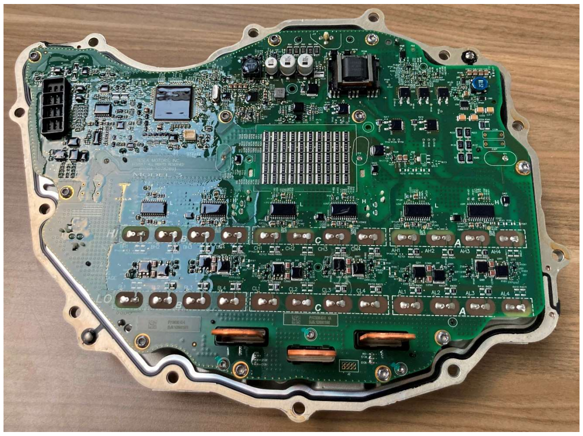
Circuit diagram of a Traction Motor Drive Inverter

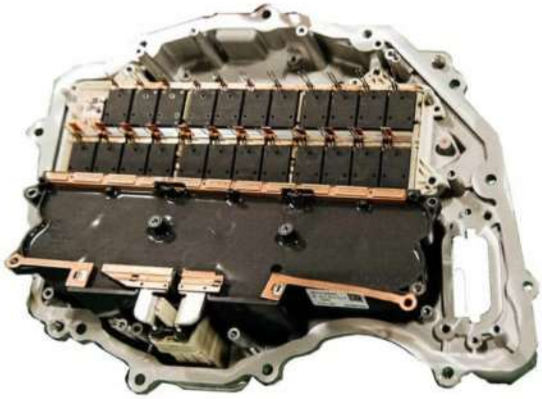


Entire inverter assembly

- **Semiconductor switches are the key to the entire inverter**
- **Si IGBT has been dominating. Only after Tesla Model 3 adopted SiC MOSFET, the entire EV industry just woke up and discovered the cost-benefit that justifies the use of SiC!**
- **The driver board mainly contains gate drivers, DSP, and auxiliary power**
- **A large capacitor bank (C_{dc}) is needed due to a long wire between battery bank and inverter circuit**
- **A bleeding resistor bank (R_{bl}) is needed for safety concern**

Pictures of Inverter Circuit Assembly

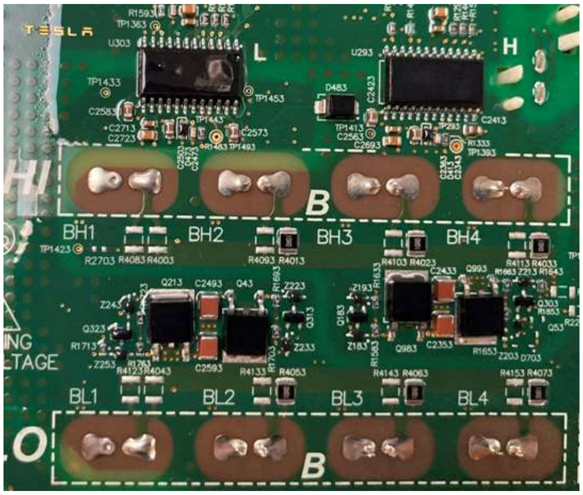




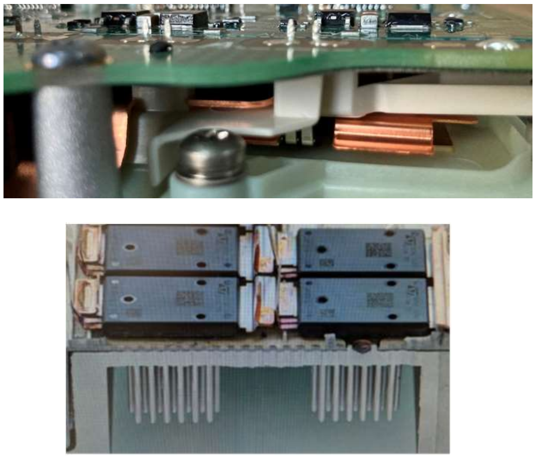
- Device: ST SiC MOSFET custom module
- Gate driver: ST Micro gate driver
- Four modules in parallel per switch
- Controller: TI320F28377D

- Bus capacitor: custom shape to fit package
- One module is not populated for most cars
- Bus bar limits the continuous current
- Bleeding resistor bank is cooled through thermal pad

Power Stage Devices, Gate Drives, Busbar

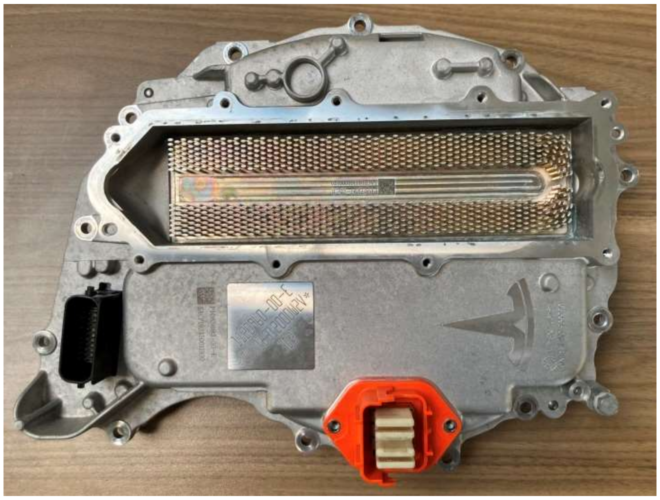


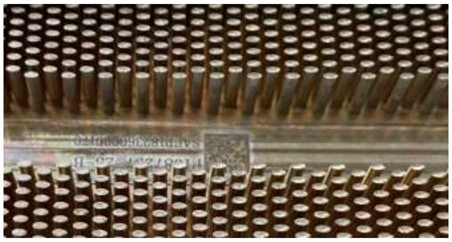
- Phase B as example showing device and gate driver arrangement
- One set of modules is disabled by removing its gate drive resistance



- Heavy bus-bars ensure sufficient current carrying capability
- SiC devices sit directly on top of pin fins

Tesla Model-3 Honeycomb Type Heat Sink for Device Cooling



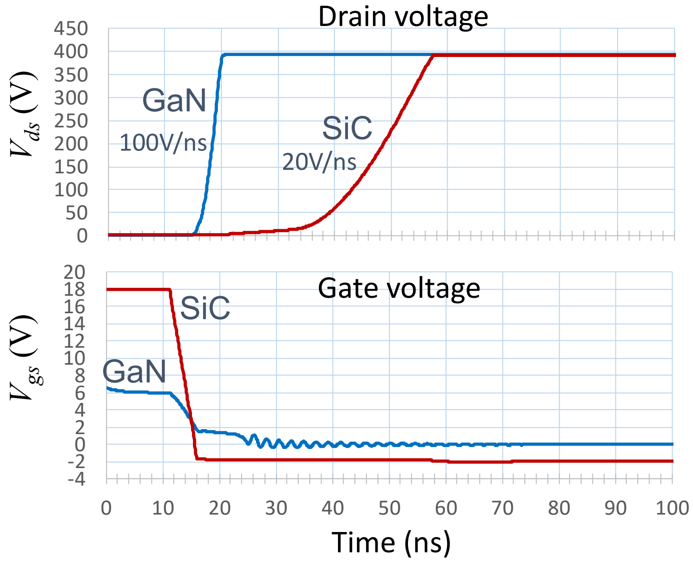


- Honeycomb heat sink to provide sufficient cooling area
- Each pin-fin is coated with silver to ensure low thermal resistance
- Bleeding resistor bank is cooled through thermal pad

Outline

- Key properties of wide bandgap (WBG) semiconductors
- Why WBG devices?
- Application examples
- **Potential issues and outlooks**

A Challenging Issue for Motor Drives – High dv/dt



- Dv/dt is related to the junction capacitance C_{oss}.
- As WBG device requires a smaller chip size for the same power rating, C_{oss} of WBG devices tends to be much lower as compared to Si devices.
- Simulation study shows dv/dt of SiC is about 20 V/ns and GaN is higher than 100 V/ns

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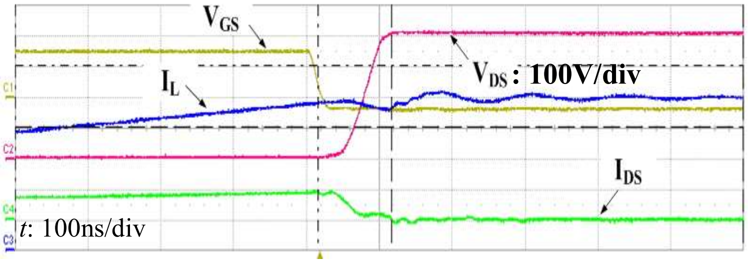
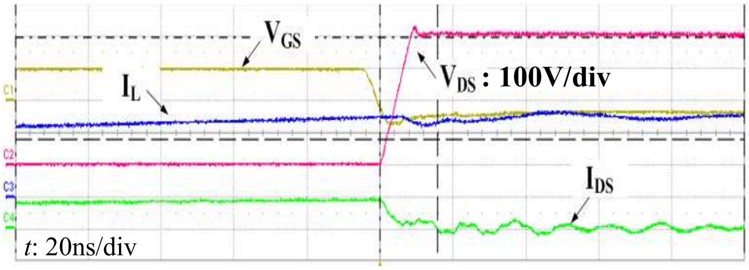
Experimental Verification of WBG Device Switching dv/dt

SiC MOSFET: SCT2120AF

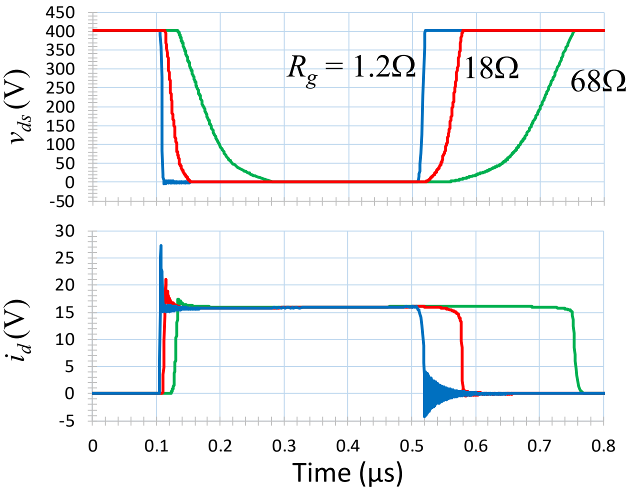


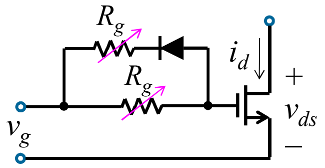
GaN HEMT: TPS3002



- Experimental results show dv/dt of SiC is about 15 V/ns and GaN is about 90 V/ns. They are slightly slower due to parasitic inductance in the loop.
- As compared to Si IGBT typically at <10 V/ns, dv/dt caused by WBG devices will worsen
  - Voltages spikes induced by long cable transmission lines,
  - bearing circulating current,
  - capacitive coupled current,
  - EMI, etc.

Switching Energy under Different Slew Rates





Turn-on

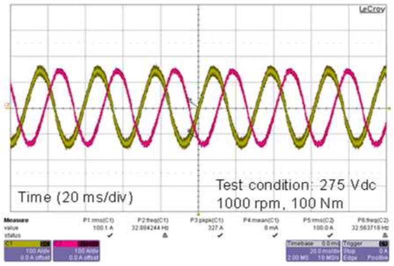
dv/dt (V/ns)	E_{on} (nJ)
100	30
40	82
4	320

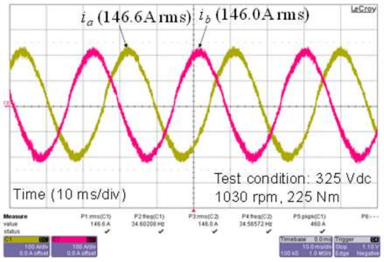
Turn-off

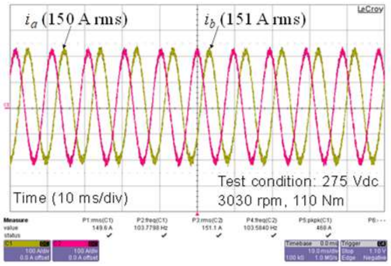
dv/dt (V/ns)	E_{off} (nJ)
133	18
13.3	112
4	1050

- **Adjusting gate drive resistance allows the control of slew rates**
- **Reducing turn-on slew rate by 25X, loss is increased by ≈10X**
- **Reducing turn-off slew rate by 33X, loss is increased by ≈60X**
- **Good to keep high dv/dt, but what about noises and capacitive coupling?**

Output Currents under Different Speed and Torque Conditions with Slow dv/dt IGBT Traction Drives



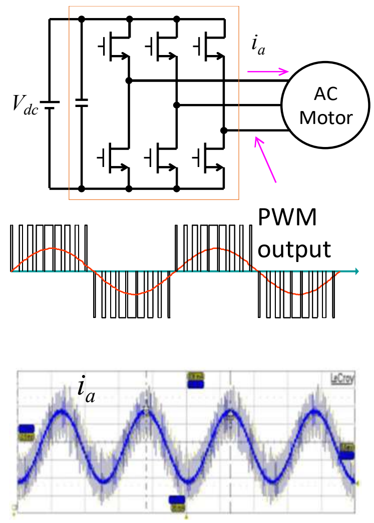




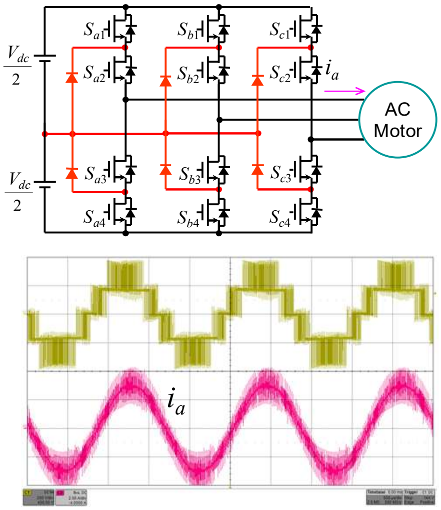
- Low speed, low torque and different bus voltages
- Low speed, high torque, nominal voltage condition
- High speed, low torque, low voltage condition

- By slowing down the switching speed, the conventional IGBT traction motor drives can avoid dv/dt induced CM noise currents
- Test conditions under different torque and speed conditions verified the possibility, but with SiC drives, such a design trade-off can compromise the switching losses

Capacitive Coupled Noisy CM Currents with High dv/dt



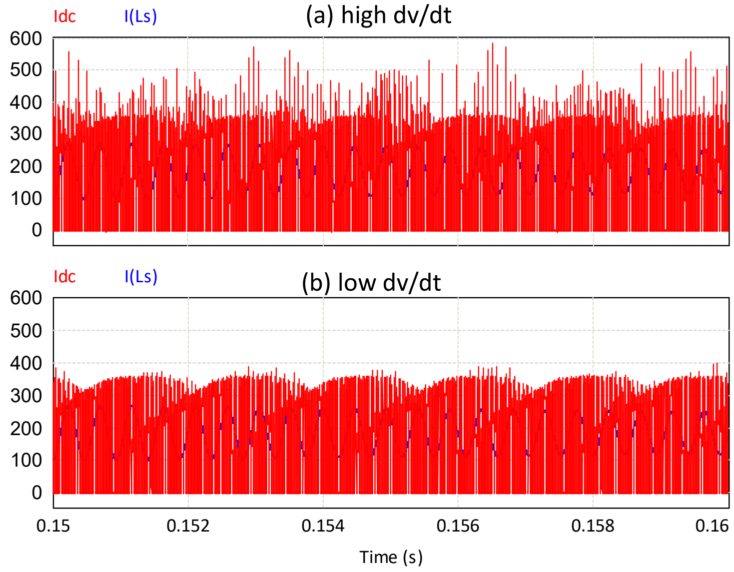
Experimental PWM current



Experimental 3-level output

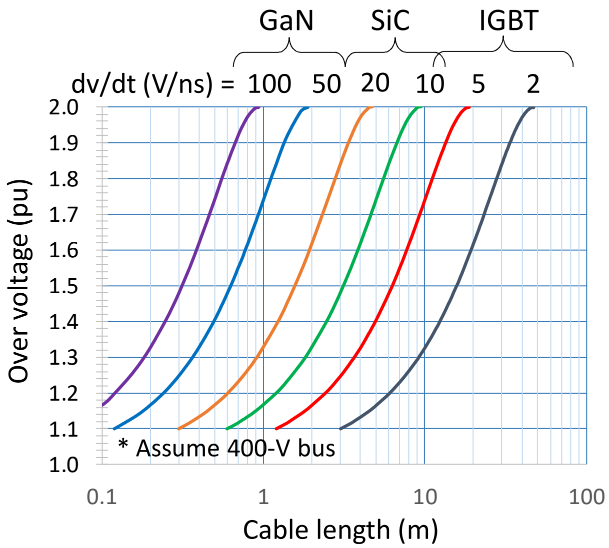
- Due to Motor winding capacitance and high dv/dt, the motor current presents severe noises (EMI)
- Even with three-level inverter to drop the voltage to half, the slew rate remains the same
- The noise can result in additional losses and nuisance gate signal tripping

EMI Noise CM Current Reflected Back to DC Bus Capacitors



- **CM current noise due to high dv/dt will be reflected to DC bus, and capacitors need to absorb them as an additional burden**
- **How to reduce capacitive coupled current while not increasing switching loss is a major design challenge**

Voltage Overshoot vs. Cable Length under Different dv/dt Conditions

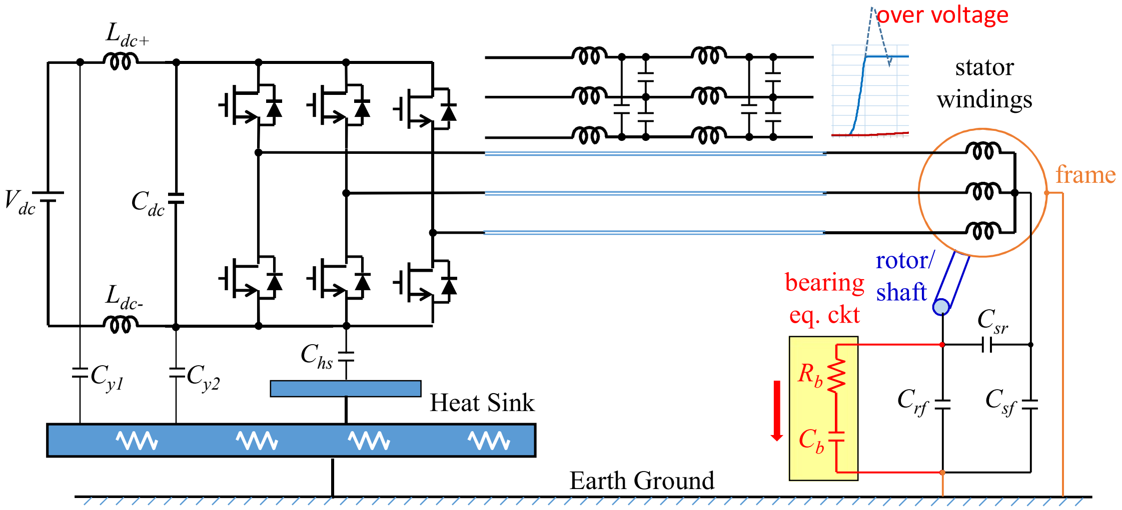


- The transmission line effect due to the long cable between inverter and motor is a well-known phenomenon for the Si-IGBT drives.
- The motor terminal sees twice voltage typically between 10 and 100 meters with conventional IGBT drives, resulting motor insulation breakdown.
- For the SiC based drives, the voltage can double if cable length is longer than 5 meters
- For the GaN based drives, under 100 and 50 V/ns conditions, the voltage doubles at 1 and 2 m, respectively

A Typical Motor Drive with a Long Cable Between Inverter and Motor

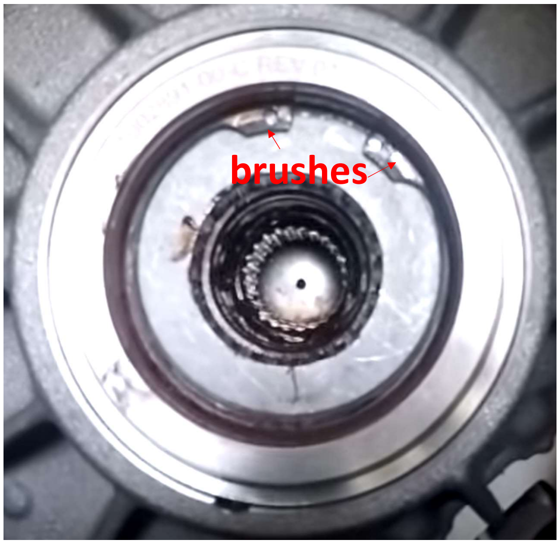
With high dv/dt, some unexpected issues arise:

1. Motor terminal over-voltage ➔ due to the long cable transmission line effect
2. Bearing parasitic capacitance induced circulating current (C·dv/dt)



How about Bearing Circulating Current?

- The parasitic capacitances along with fast dv/dt create a circulating bearing current and damage the bearing balls
- There are many solutions to alleviate such a current.
- Slowing down switching is not preferred as it increases loss substantially.
- However, fast switching will result in a significant current caused by C·dv/dt or common mode (CM) current
- The solution used by Tesla is to add brushes to bypass such a CM current through the shaft to ground
- Not elegant, but a tradeoff !!!



Photograph from Tesla Model S

Summary of Design Challenges Due to "Good" Features of WBG Devices

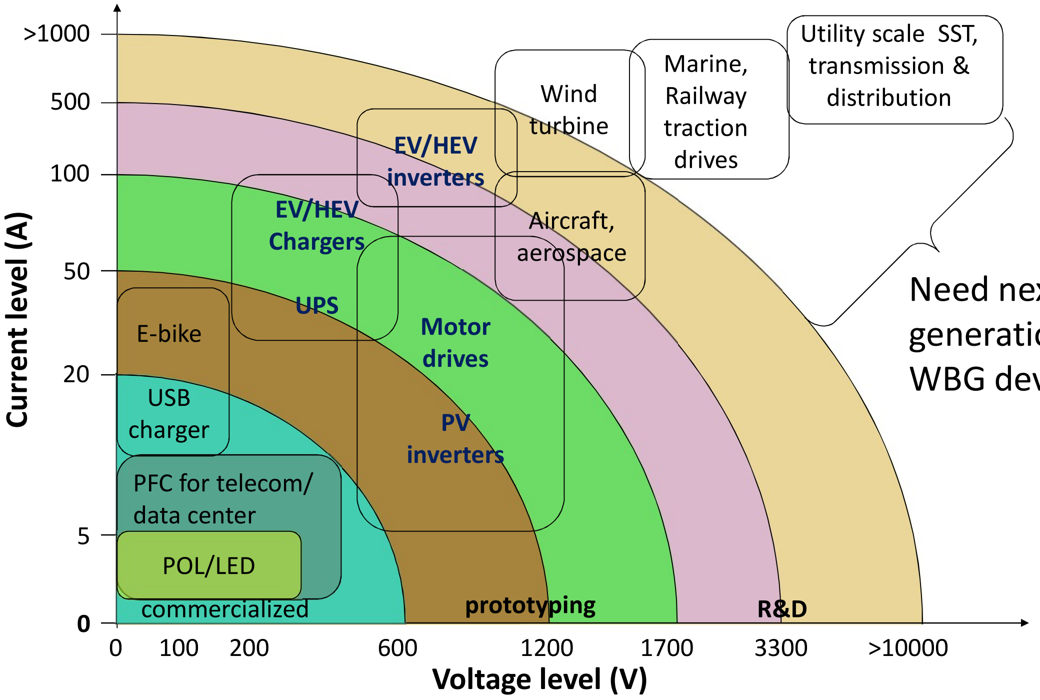
"Good" Features	Induced issues	Design Challenges
Low conduction voltage drop ➔ low conduction loss	$\Delta R_{ds\text{-}on} \propto \Delta T_j$	High $R_{ds\text{-}on}$ at operating temperature
	Small chip size	Reduced short ckt current capability
		Reduced avalanche capability
Fast switching ➔ low switching losses	High dv/dt	Induced motor winding over voltage
		Induced bearing circulating current
	High CM current	Over burden DC bus capacitors

Outlook – Development Trends on Wide Bandgap Devices

- **Cost remains a major concern but is showing signs of significant decline over the last decade.**
- **Niche applications such as PFC, high-end power supplies, and high-efficiency PV inverters have adopted SiC Schottky diodes to meet stringent standards.**
- **Further justification of WBG switches need to include system level cost that includes heat sink, magnetic components, and capacitors.**
- **GaN devices are showing more promising Figure of Merit and potentially low cost. Once the reliability is proven, significant usages will occur in higher power territories.**
- **Integration trend**
  - Gate drive + GaN FET and GaN half-bridge module (TI)
  - Integrated GaN FET and controller (Navitas, Power Integration)
  - High power module (Wolfspeed)
  - Bare die available for custom integration (EPC, Rohm, Wolfspeed)
- **Wafer development**
  - GaN wafer is on the way
  - 8” SiC wafer plant has been inaugurated by Wolfspeed

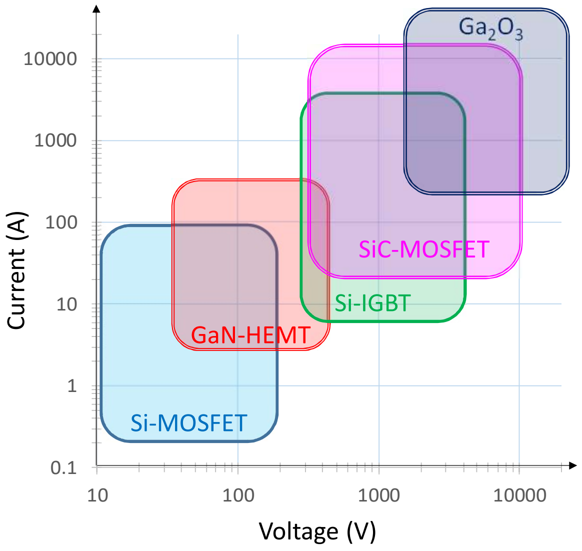
8” wafer to be manufactured by Wolfspeed

Power Electronics Applications vs. Device VA Ratings



Need next generation WBG devices

Voltage and Current Ranges of WBG Devices



- Si MOSFET: switching power supplies
- GaN: high freq., compact size, production already started for home/office and renewable energy such as PV applications
- Si IGBT: motor drives, industrial applications
- SiC: high-voltage, high-power, production already started for EV traction motor drives
- Diamond (C), Aluminum Nitride (AlN), Gallium trioxide (Ga_2O_3) are still in research stage, but Ga_2O_3 has stood out for a faster pace toward realization: very high-voltage, very high-power for utility-scale (>10kV) applications

Recap

- **WBG devices are “revolutionizing” the entire energy and power industry.**
- **To take advantages of WBG devices, a whole new set of knowledge base is needed to deal with small chip size and fast switching rate, including PCB layout, parasitic extraction, EMI, protections, thermal management, etc.**
- **SiC and GaN devices came out available in the market nearly the same time. At 600-V level, they seem to be in competition, but they also tend to have significant appearance in different applications.**
  - **SiC goes into high power such as motor drives where switching frequency doesn’t need to be ultrahigh**
  - **GaN goes into high-frequency chargers where power density and passive component size reduction are critical**
- **Cost and performance will determine which device is to be adopted. The chip level cost reduction can be expected with larger-size wafers on the way.**

Questions

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