# Advanced semiconductor solutions for a hot future in heat pumps

November 2022

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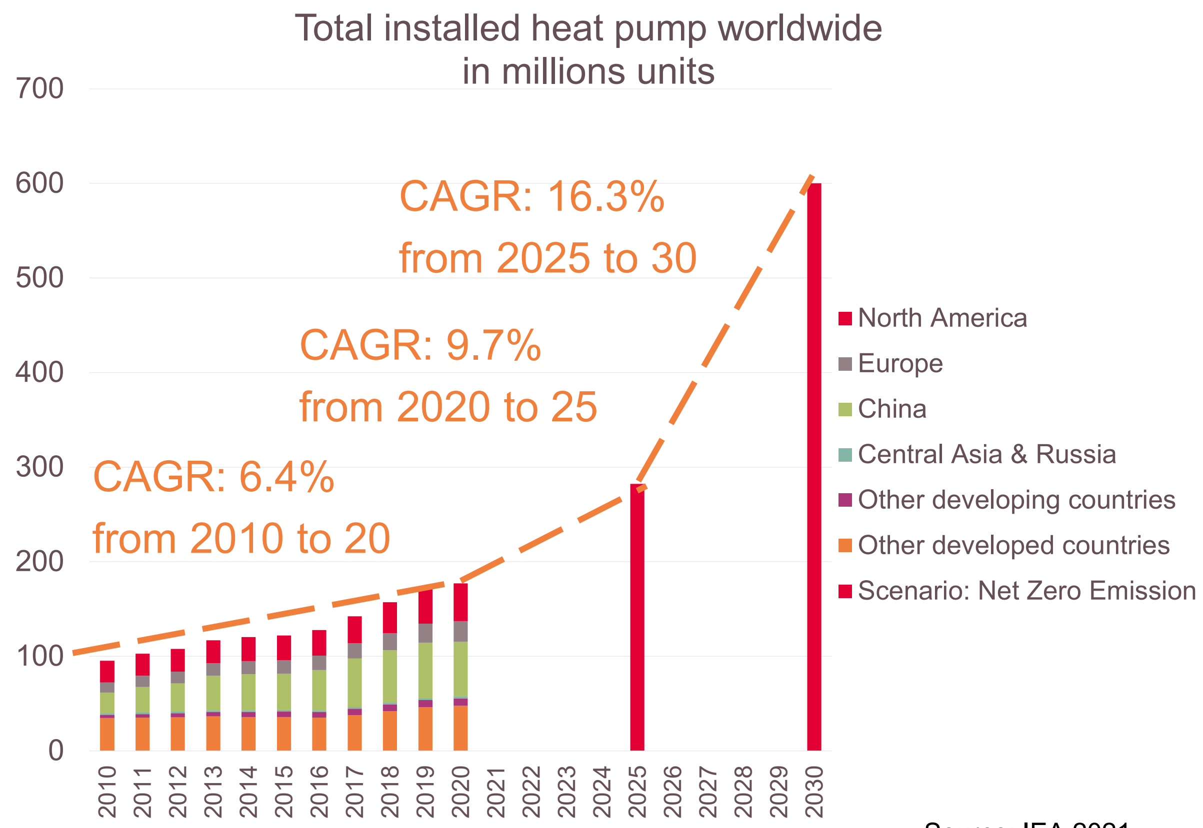
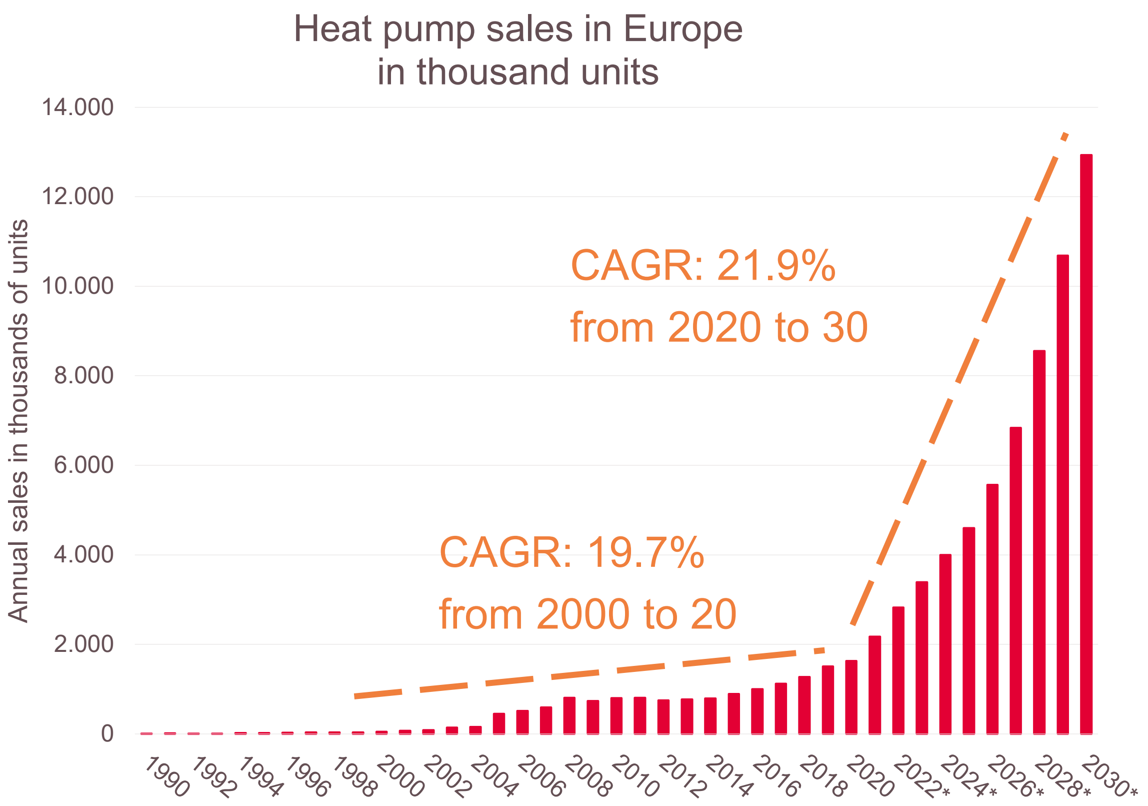
# Booming heat pump market in the world and Europe

**Regulation due to the goal of net zero emission is the reason for the increase in heat pump sales up to 2030**

**Heat pump market is growing since 2000 with CAGR of 19.7% and expected sales of 12.9 million in 2030**




Source: IEA,2021




Source: European Heat Pump Association, 2022

# Market segmentation of heat pump according heating power

| Application market segments | | | | | |
|---|---|---|---|---|---|
| Heating power | | Overview electrical power requirement | | | |
| | | Voltage supply | Compressor | Circu. pump | Fan |
| Residental to commercial | 2 kW to 8 kW | 230 V/ 1 PN/ 50 Hz | < 3 kW | < 60 W | < 125 W |
| | 8 kW to 13 kW | 230 V/ 1 PN/ 50 Hz | < 4 kW | < 180 W | < 230 W |
| | | 400 V/ 3 PN/ 50 Hz | < 5 kW | | |
| | 13 kW to 20 kW | 400V/ 3 PN/ 50 Hz | < 8 kW | < 300 W | < 290 W |
| Commercial | > 20 kW | 400 V/ 3 PN/ 50 Hz | > 8 kW | > 500 W | > 580 W |

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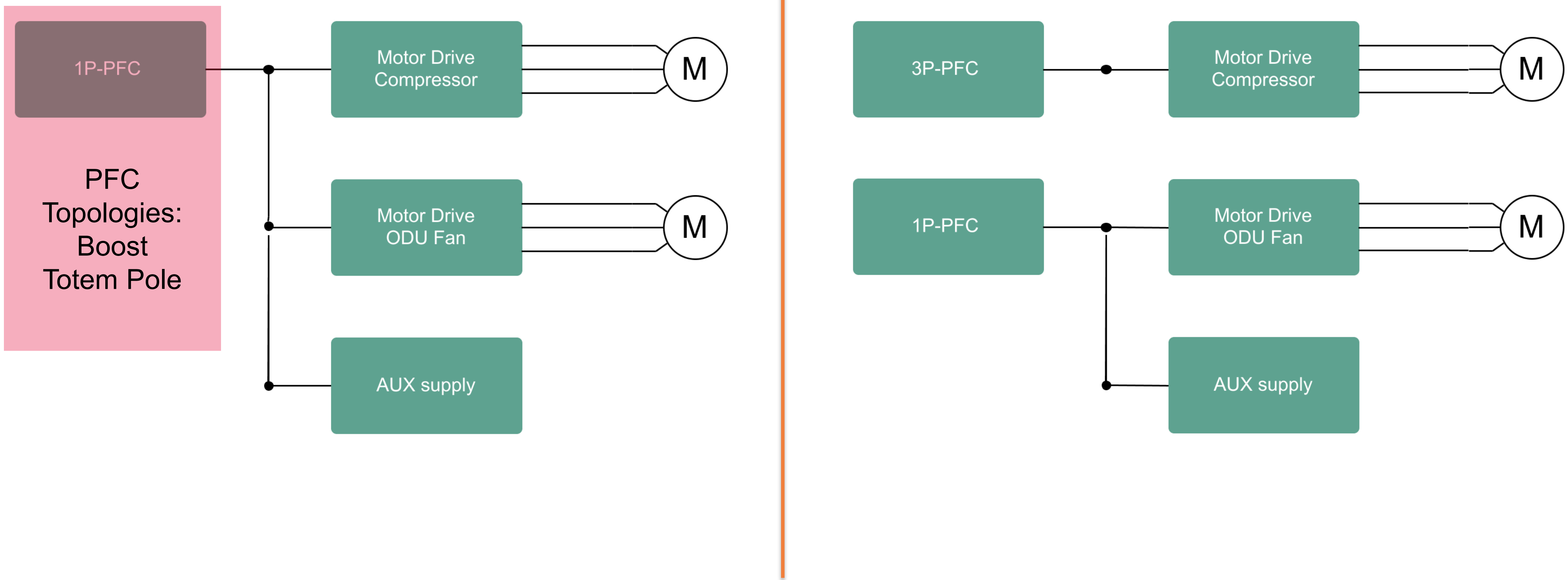
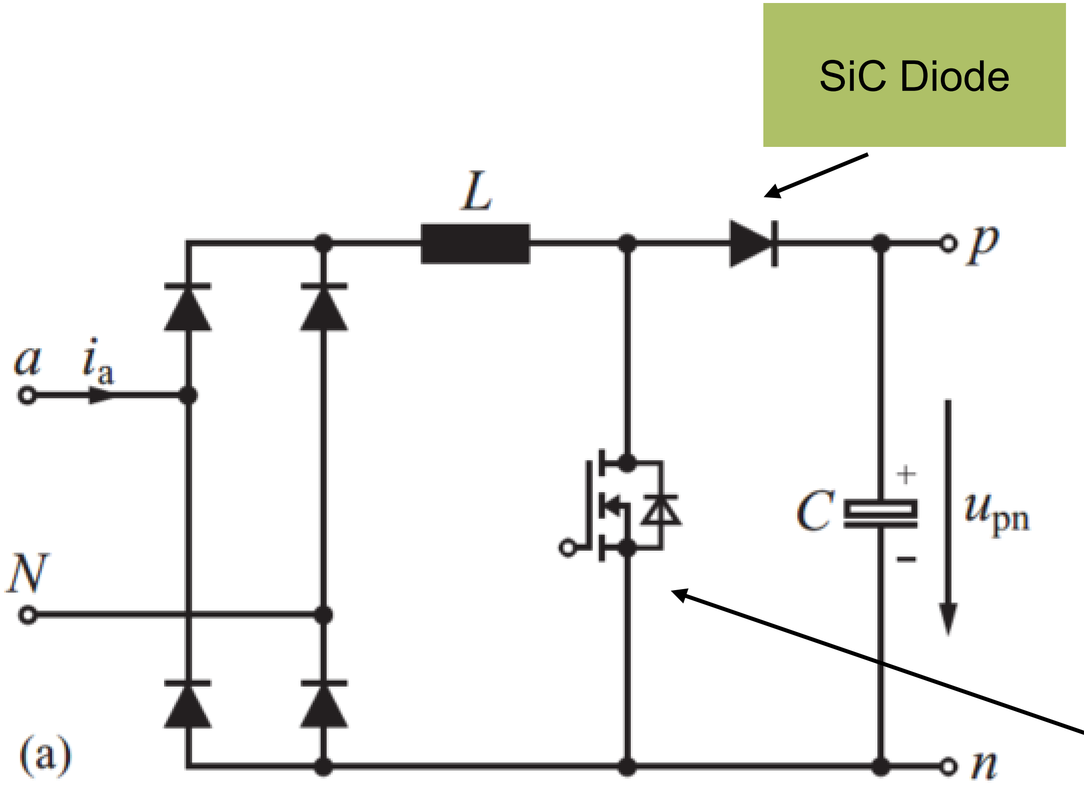
# Simplified heat pump power block diagram

Heat pump outdoor unit



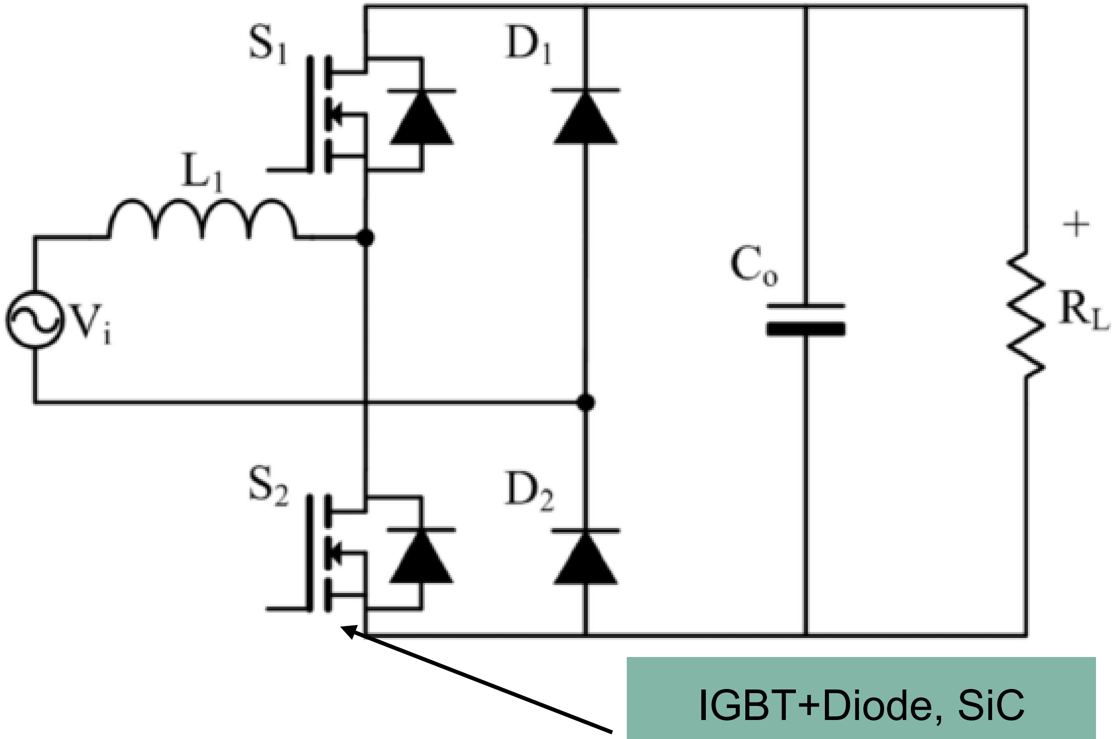
# 1-phase PFC topologies – CCM boost




- Requires bridge rectifier
- Single unidirectional switch + diode
- Simple control
- Moderate efficiency
- Optional interleaving
  - Reduced ripple
  - Reduced inductor losses
  - Reduced switch losses
  - Increased part count

Image Source: J. W. Kolar and T. Friedli, "The Essence of Three-Phase PFC Rectifier Systems—Part I," in IEEE Transactions on Power Electronics, vol. 28, no. 1, pp. 176-198, Jan. 2013, doi: 10.1109/TPEL.2012.2197867.

# 1-phase PFC topologies – Totem pole

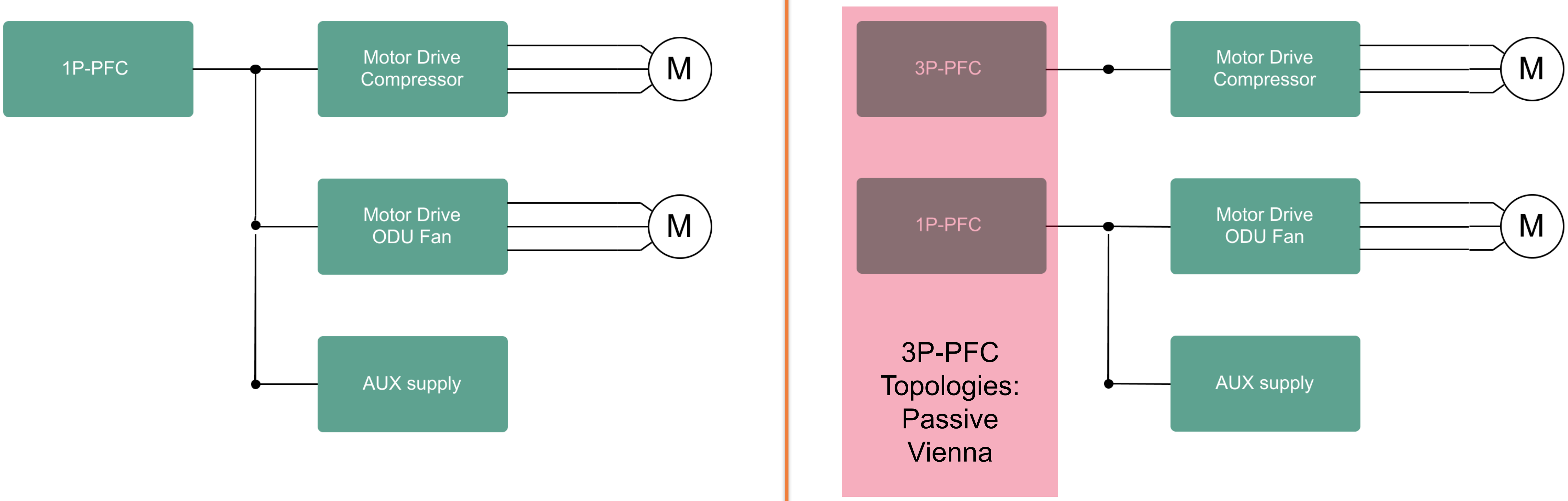



IGBT+Diode, SiC MosFET, GaN

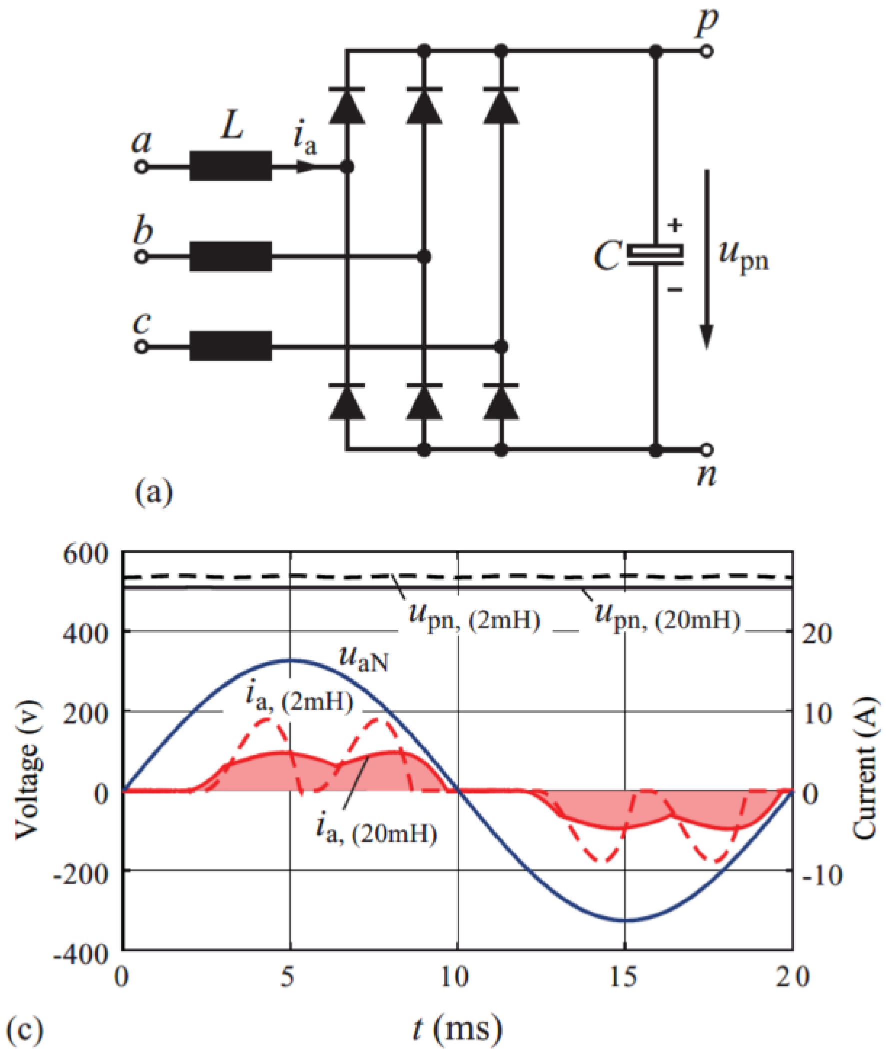
- No bridge rectifier
- Requires two bidirectional switches
- High efficiency
- High power density
- Optional interleaving
  - Reduced ripple
  - Reduced inductor losses
  - Reduced switch losses
  - Increased part count

Image Source: https://www.researchgate.net/publication/45573039_An_Interleaved_Totem-Pole_Power_Factor_Correction_Converter

# Simplified heat pump power block diagram



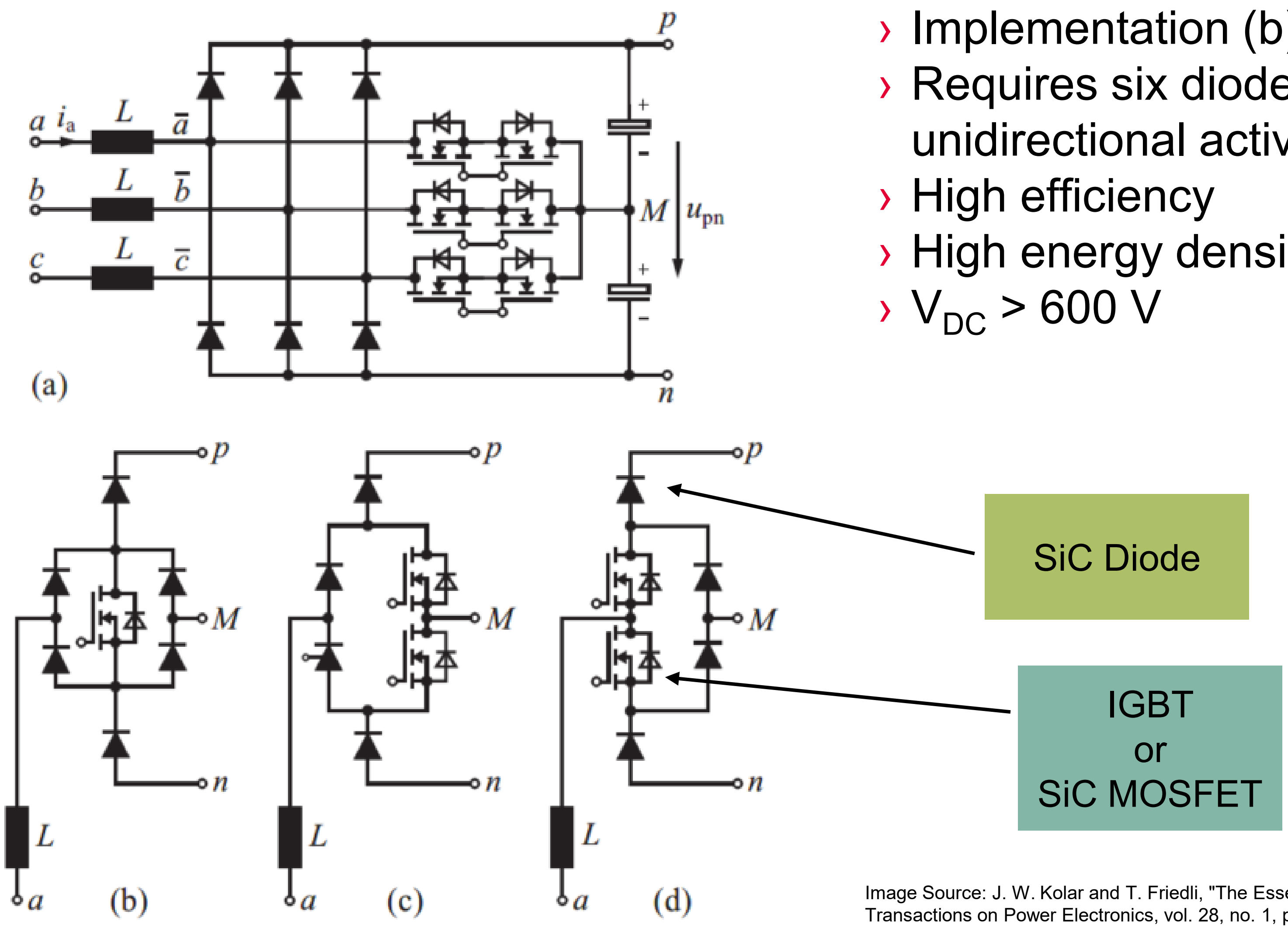
# 3-phase PFC topologies – Passive




- › Requires 2 diodes per phase
- › No active switch required
- › Moderate losses in inductor & diodes
- › Low PF
- › $V_{DCnom}$ < 600 V

Image Source: J. W. Kolar and T. Friedli, "The Essence of Three-Phase PFC Rectifier Systems—Part I," in IEEE Transactions on Power Electronics, vol. 28, no. 1, pp. 176-198, Jan. 2013, doi: 10.1109/TPEL.2012.2197867.

# 3-phase PFC topologies – Vienna rectifier




- Implementation (b) is most common
- Requires six diodes per phase and one unidirectional active switch
- High efficiency
- High energy density
- $V_{DC}$ > 600 V

Image Source: J. W. Kolar and T. Friedli, "The Essence of Three-Phase PFC Rectifier Systems—Part I," in IEEE Transactions on Power Electronics, vol. 28, no. 1, pp. 176-198, Jan. 2013, doi: 10.1109/TPEL.2012.2197867.

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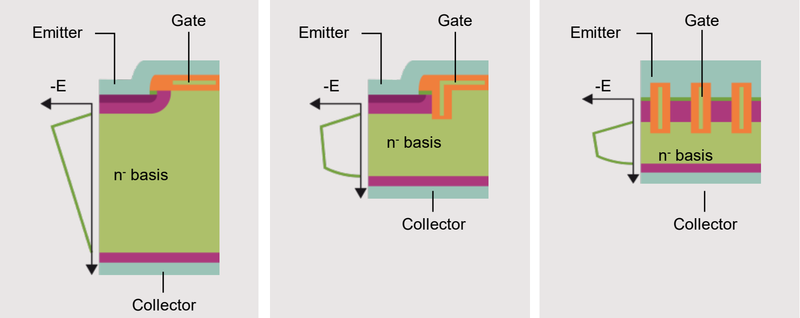
# Infineon 1200 V IGBT 7 S7
# The new generation short-circuit robust IGBT

**40 A 1200 V low speed IGBT**
**Total switching loss (mJ) vs Vce(sat) @ Tc=25 °C)**

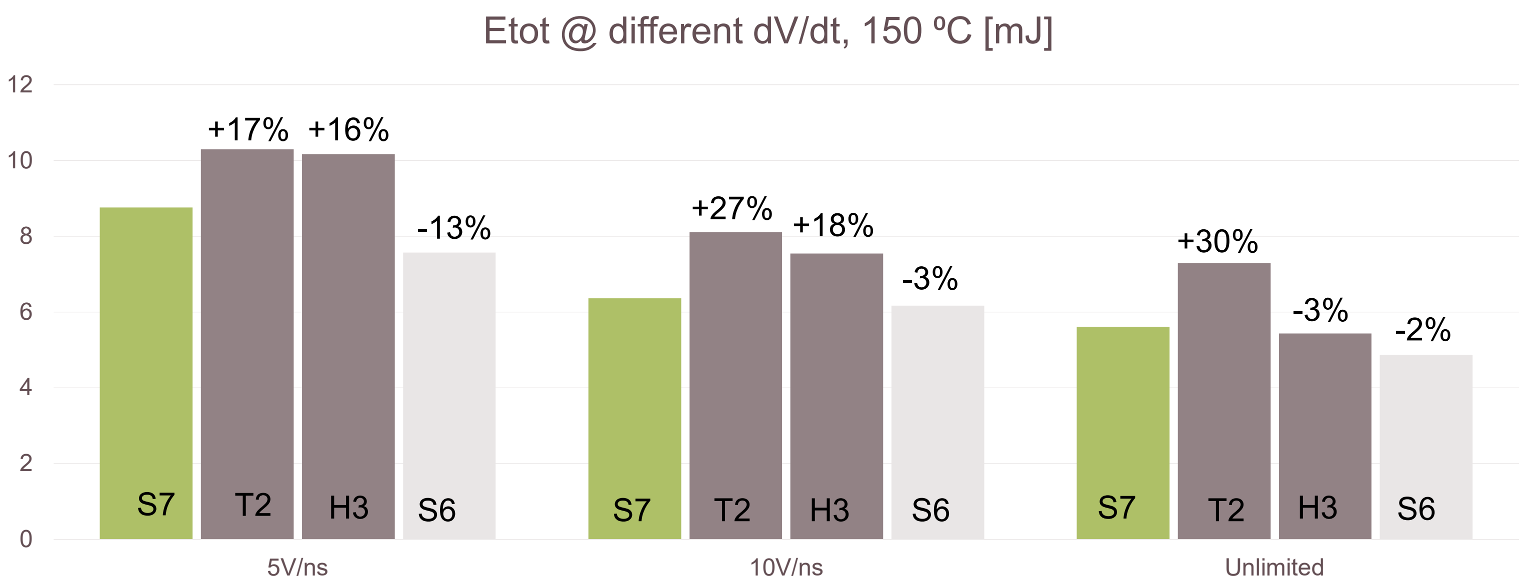

| Non Punch Through<br>Infineon IGBT2 | Trench Field Stop<br>Infineon IGBT3 … 4 | Micro Pattern Trenches<br>Infineon IGBT7 |
|---|---|---|
| (Infineon 1990 ROW: 1997) | (Infineon 2000 ROW: 2006) | (Infineon new generation) |



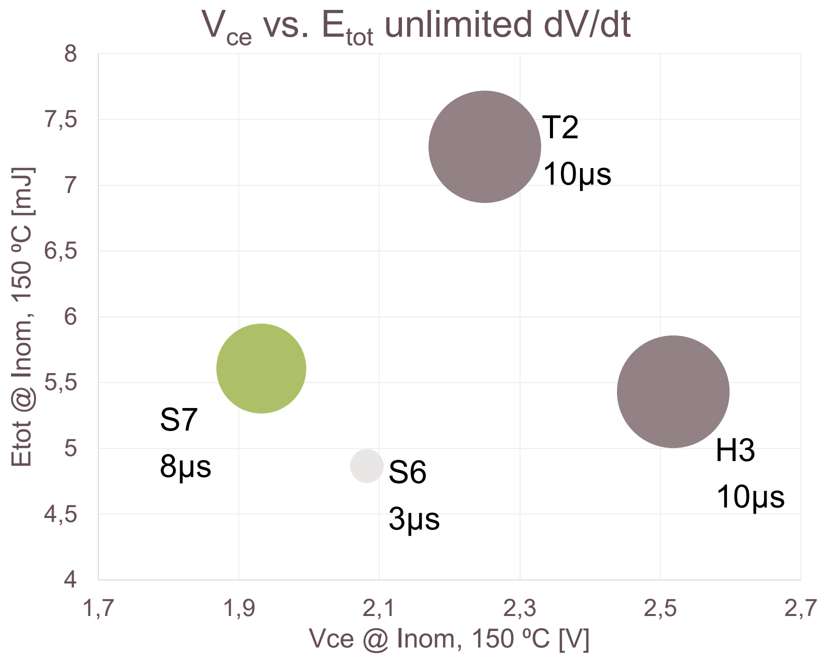

| Non Punch Through | Trench Field Stop | Micro Pattern Trenches |
|---|---|---|
| **Advantages**<br>› Implanted Back-Emitter<br>› Better adjustable | **Advantages**<br>› Implanted Back-Emitter<br>› Thinner Base Region | **Advantages**<br>› Highly adjustable Emitter<br>› Carrier Profile Optimization |
| **Performance**<br>› Low Switching losses<br>› Robustness | **Performance**<br>› Lower VCEsat<br>› Lower Switching losses | **Performance**<br>› Very low VCEsat<br>› Very low switching losses<br>› Humidity rugged |

**The best-in-class MPT technology of IGBT7 S7 allows reduction of both Vce(sat) by ~ 10% and total switching losses up to 30% lower than previous generations**

# Infineon 1200 V IGBT 7 S7
# Total switching loss (Etot): 16~27% lower than T2, H3 @ 5~10V/ns

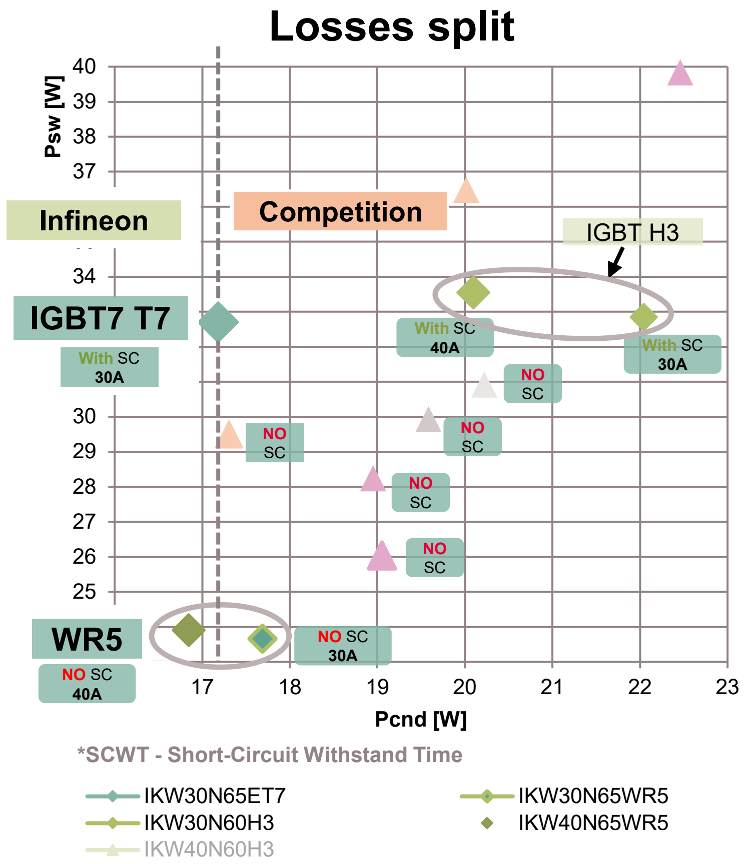


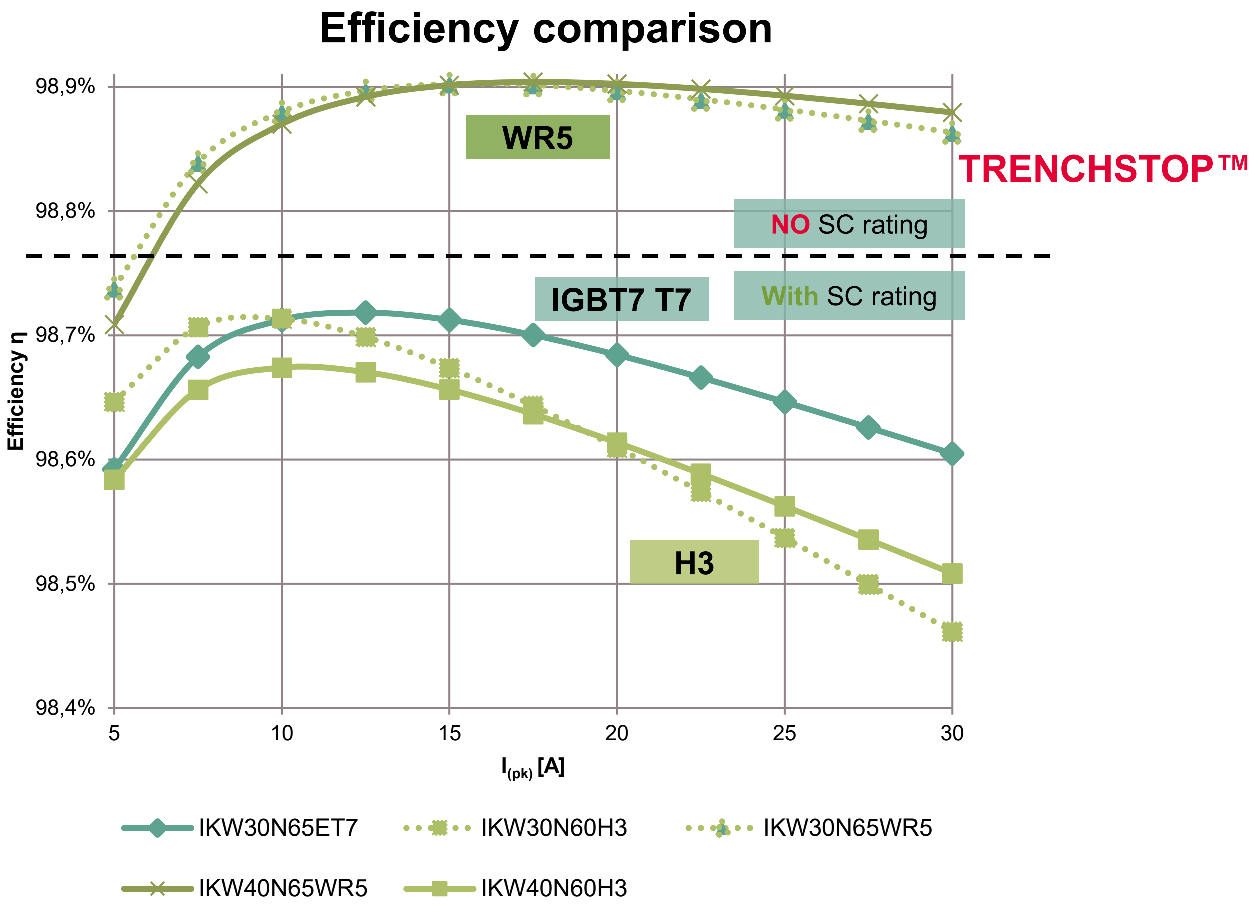

Tested with IKW40N120CS7, IKW40N120CS6, IKQ40N120CH3, IKW40N120T2,
$V_{dc}$ = 600V, I = 40A, including co-packed diode reverse recovery loss




- S7 generation ahead of T2 and H3
- S7 has similar tradeoff curve as S6, but much larger SC withstand time

# 650 V TRENCHSTOP™ IGBT7 T7 in PFC topology




**Infineon offer the best-in-class devices for PFC application, with or without SCWT**

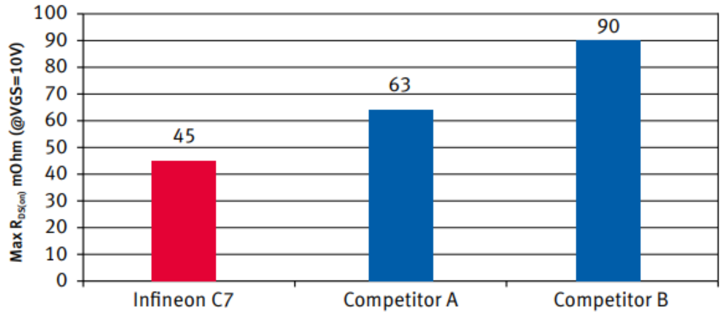
The PFC test conditions and simulation validation, for details and complete of application tests look appendix
Iin(pk)=16 Arms, Vin=180 Vrms, Vout=400 V, Vin=180 Vrms, Fpwm=30 kHz, Pi=3 kW, Tj=100°C, Rg(on/off)=22/10 ohm

# Infineon CoolMOS™ C7 series

**Infineon offer the best-in-class devices for PFC application**

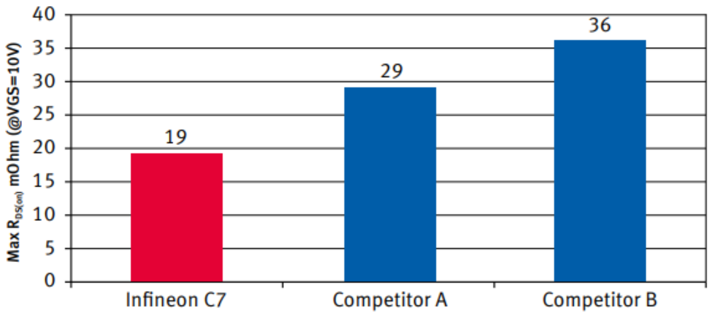
**New CoolMOS™ C7 series comparing Best-in-Class competition $R_{DS(on)}$ per package**

**650V C7 vs. Competition in TO-220 & D²PAK**

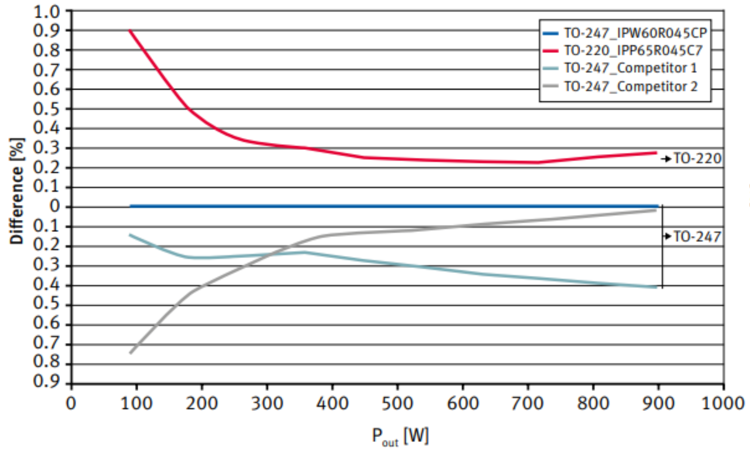


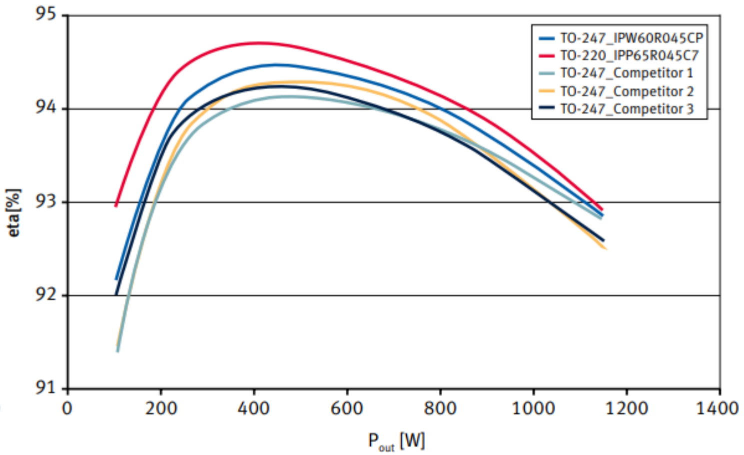

Infineon new CoolMOS™ C7 extends our lead in TO-220 & D²PAK package with a 29% lower $R_{DS(on)}$ than the nearest competitor

**650V C7 vs. Competition in TO-247**




Infineon's new CoolMOS™ C7 establishes technology leadership in the TO-247 package with a 34% lower $R_{DS(on)}$ than the nearest competitor

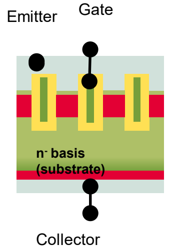


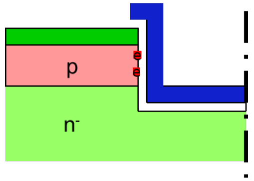
# Infineon will complement each of its leading-edge silicon solutions with a wide bandgap technology

SiC Innovation and technology leadership

## TRENCHSTOP™ to CoolSiC™

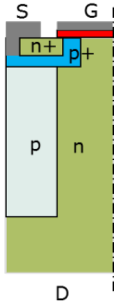



Si
IGBT

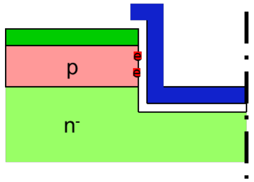



SiC
MOSFET

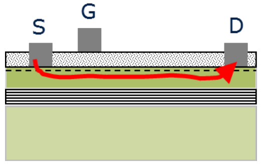
## CoolMOS™ to CoolGaN™ and CoolSiC™




Si
Superjunction

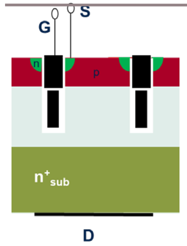



SiC
MOSFET

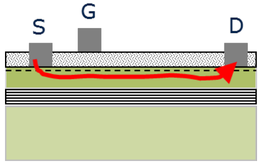



GaN
HV e-mode lateral HEMT

## OptiMOS™ to CoolGaN™



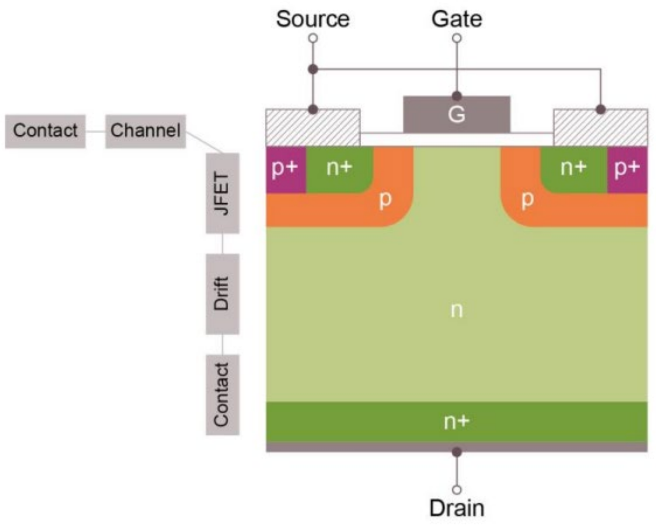

Si
Fieldplate




GaN
MV e-mode lateral HEMT

# Summary of trench versus planar in SiC

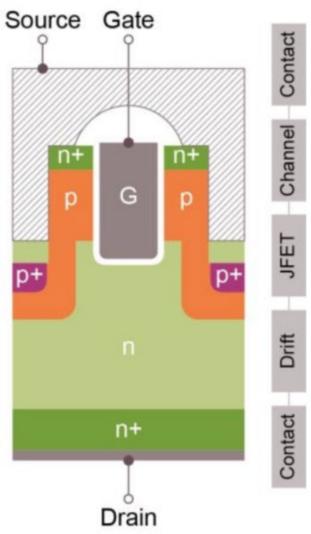
## SiC planar




- Easy/cheap process
- Good shielding of oxide possible

- Very low channel mobility
- Limited shrink options

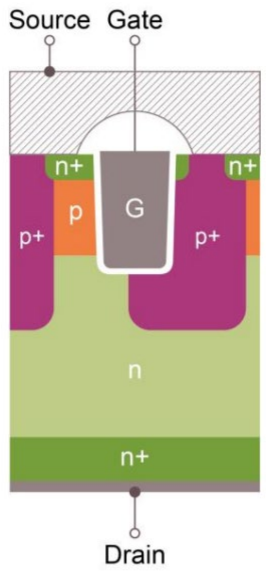
## SiC trench




- Low channel resistance
- Shrink potential higher than in DMOS

- Sophisticated process (know-how needed)
- Protection of oxide corners needed

## Infineon trench

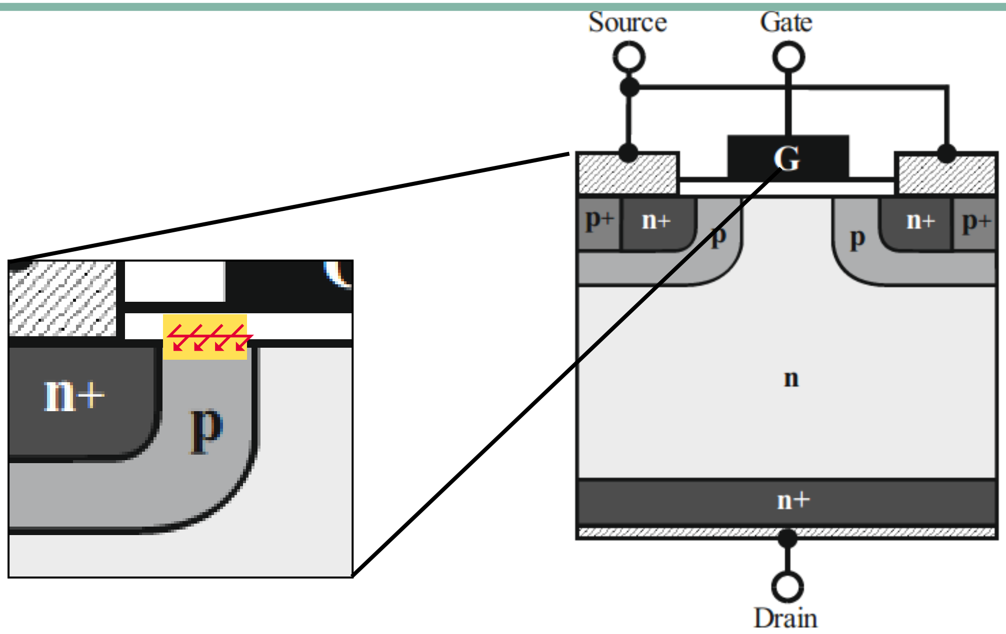



Granted by Infineon trench technology experience over > 25 years

Granted by Infineon SiC folded double trench structure

# Concept motivation trench versus planar
# Cell concept based SiC-specific interface properties

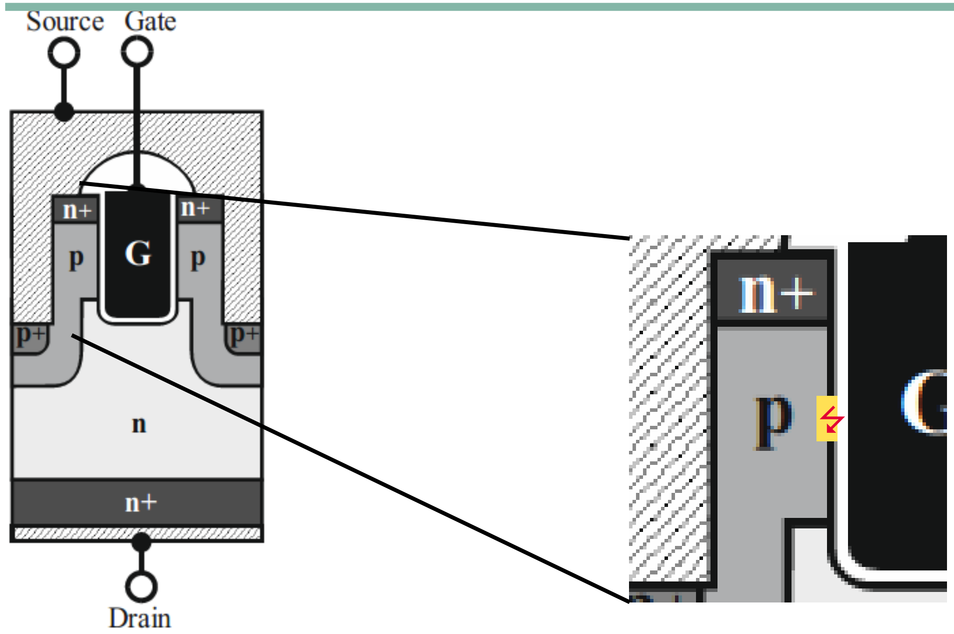
## SiC planar




- High density of defects leads to high channel resistance
- Low on-resistance achievable via high electric fields across the gate oxide
- All planar SiC MOSFETs today with more than 3 MV/cm for turn-on, low $V_{GS\_th}$ and high $V_{GS\_on}$

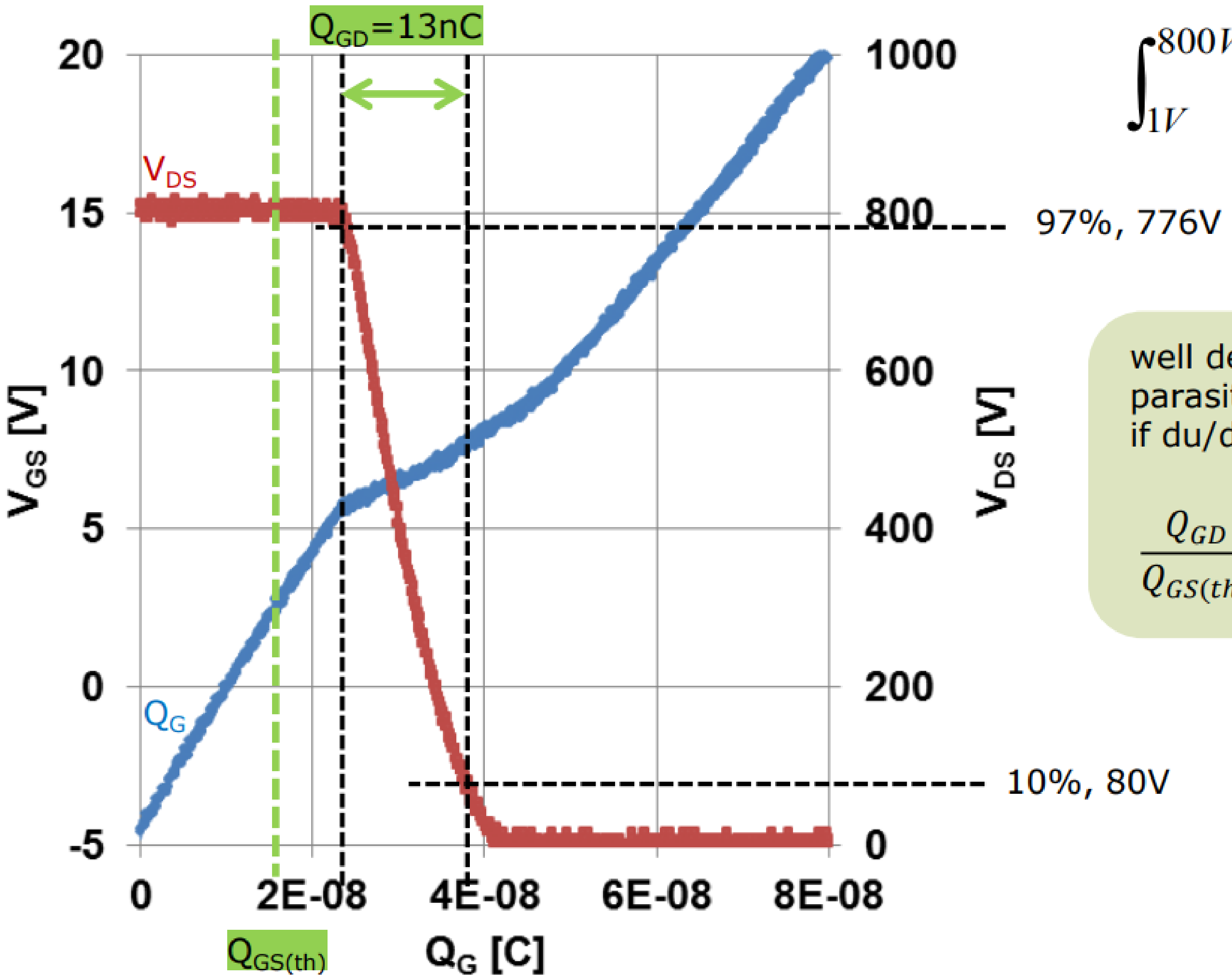
**Reliability risk !**

## SiC trench




- Low density of defects leads to low channel resistance
- Low on-resistance achieved at oxide field below 3 MV/cm
- Possible to achieve high $V_{GS\_th}$ and IGBT like $V_{GS\_on}$

# 1200 V CoolSiC™ gate charge design to counter parasitic turn-on

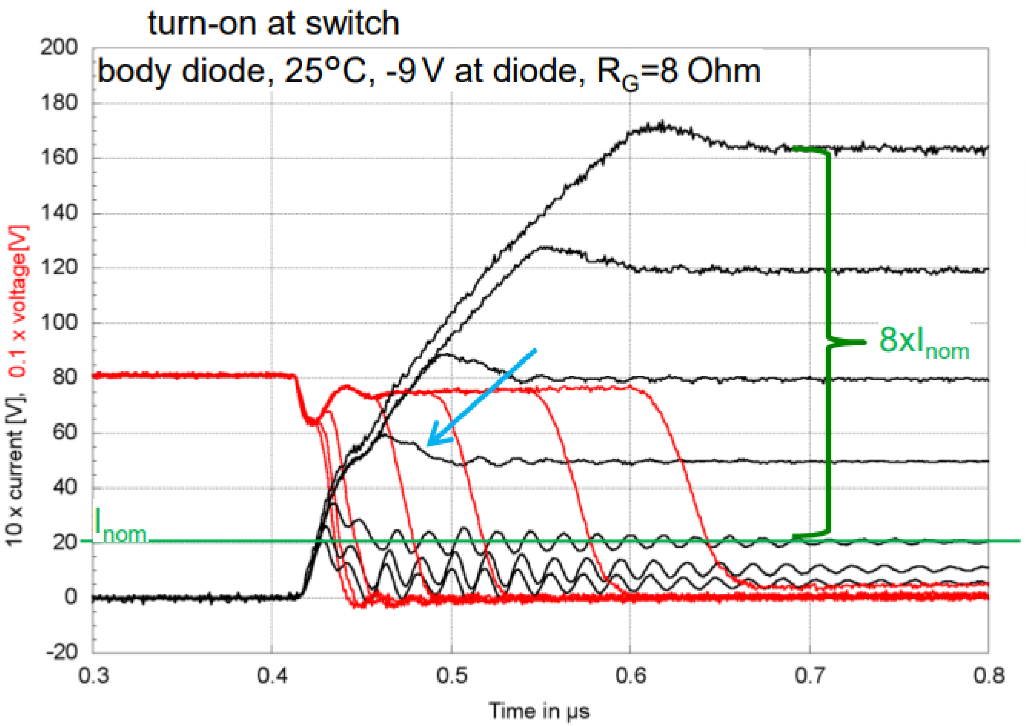



$$\int_{1V}^{800V} C_{rss}\,dV_{DS} = 12nC$$

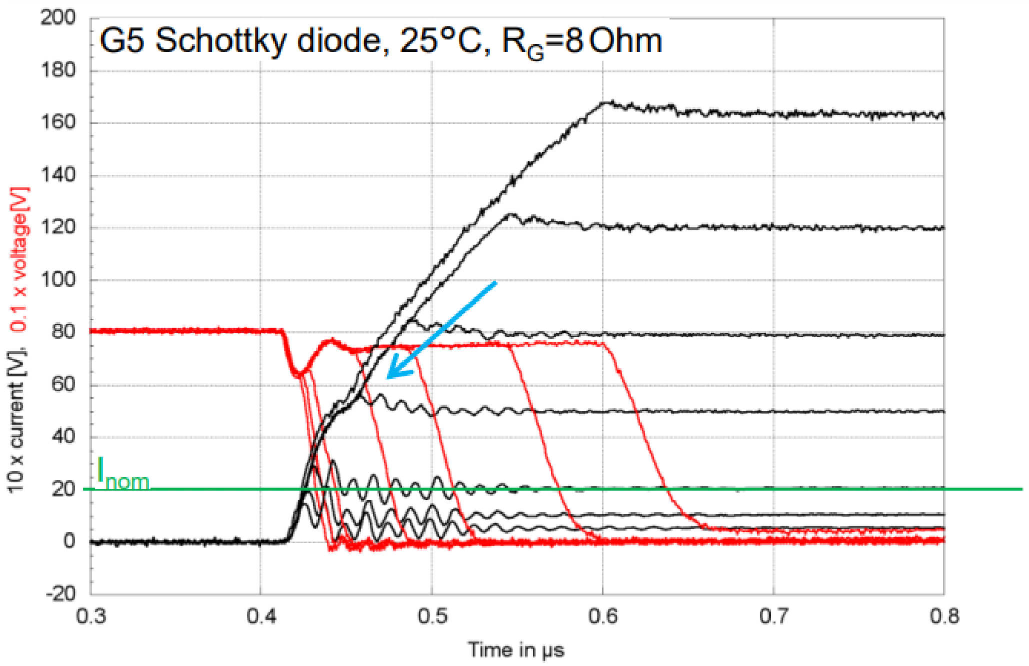
well designed to avoid parasitic return-on if du/dt high:

$$\frac{Q_{GD}}{Q_{GS(th)}} = \frac{13\ nC}{15\ nC} = 0.87$$ ☺

# 1200 V CoolSiC™ Body Diode commutation robustness, 800 V, 25°C and high currents

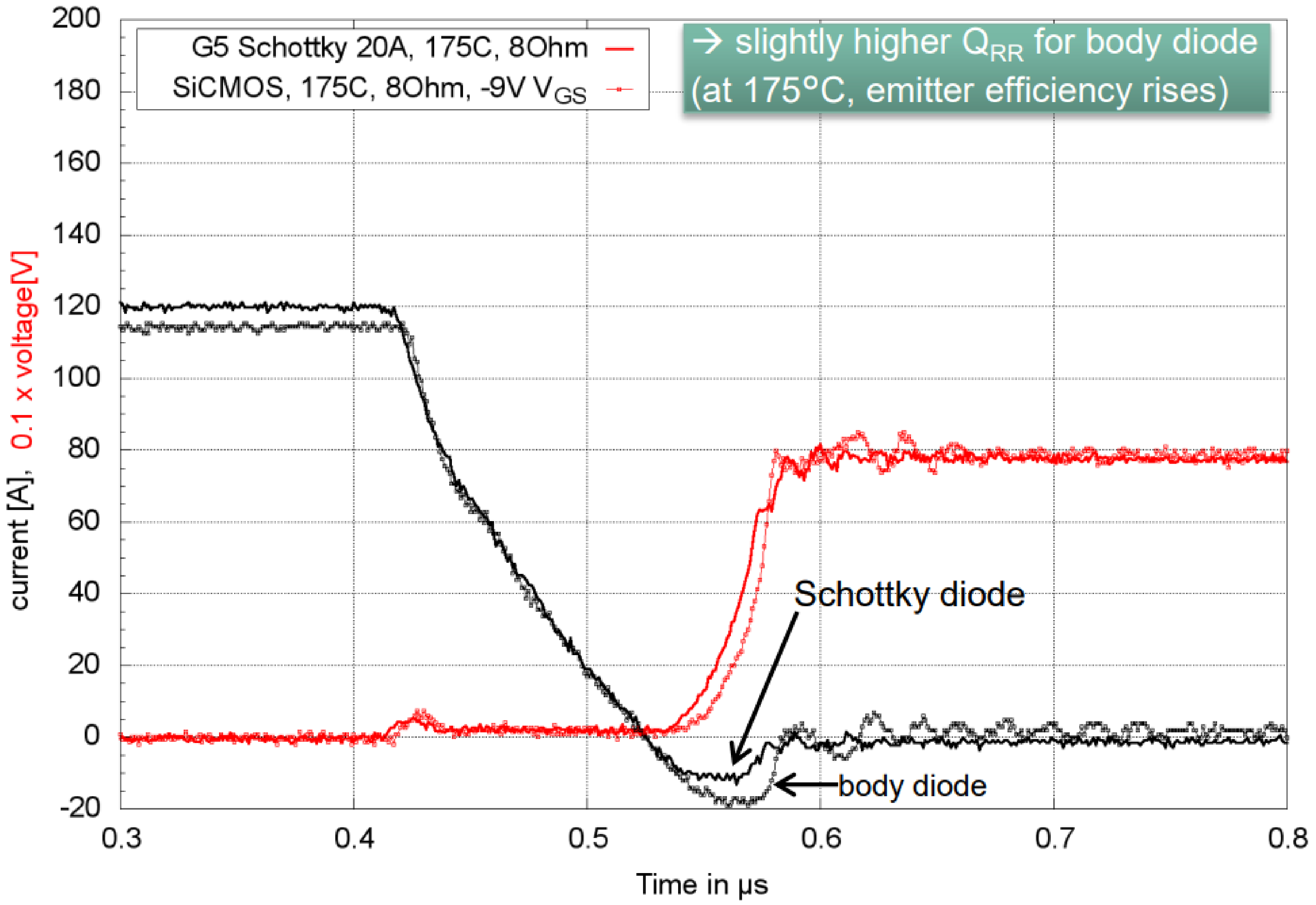



**body diode behaves similar to SiC Schottky diode**



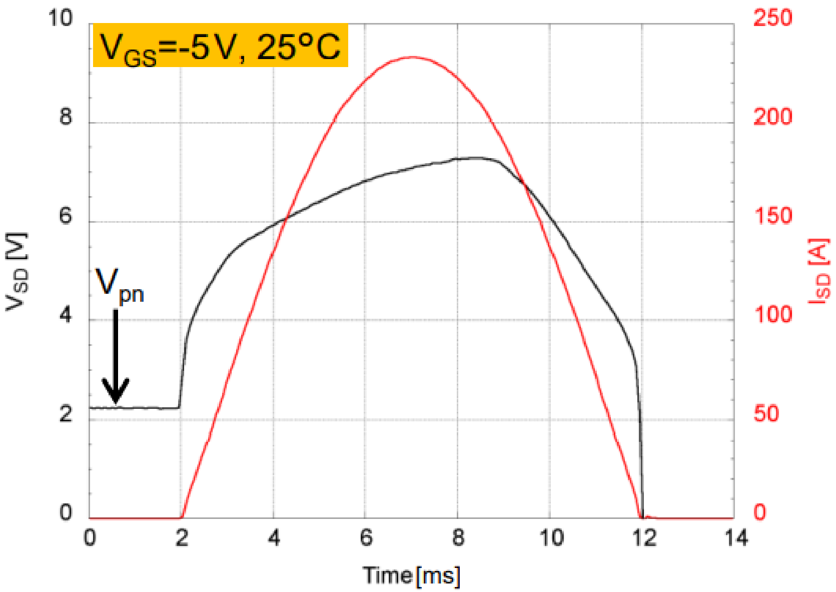

- earlier damping of oscillations (n,p) →
- wide SOA: ~4.5 times datasheet $I_{nom}$ at 800 V/100°C

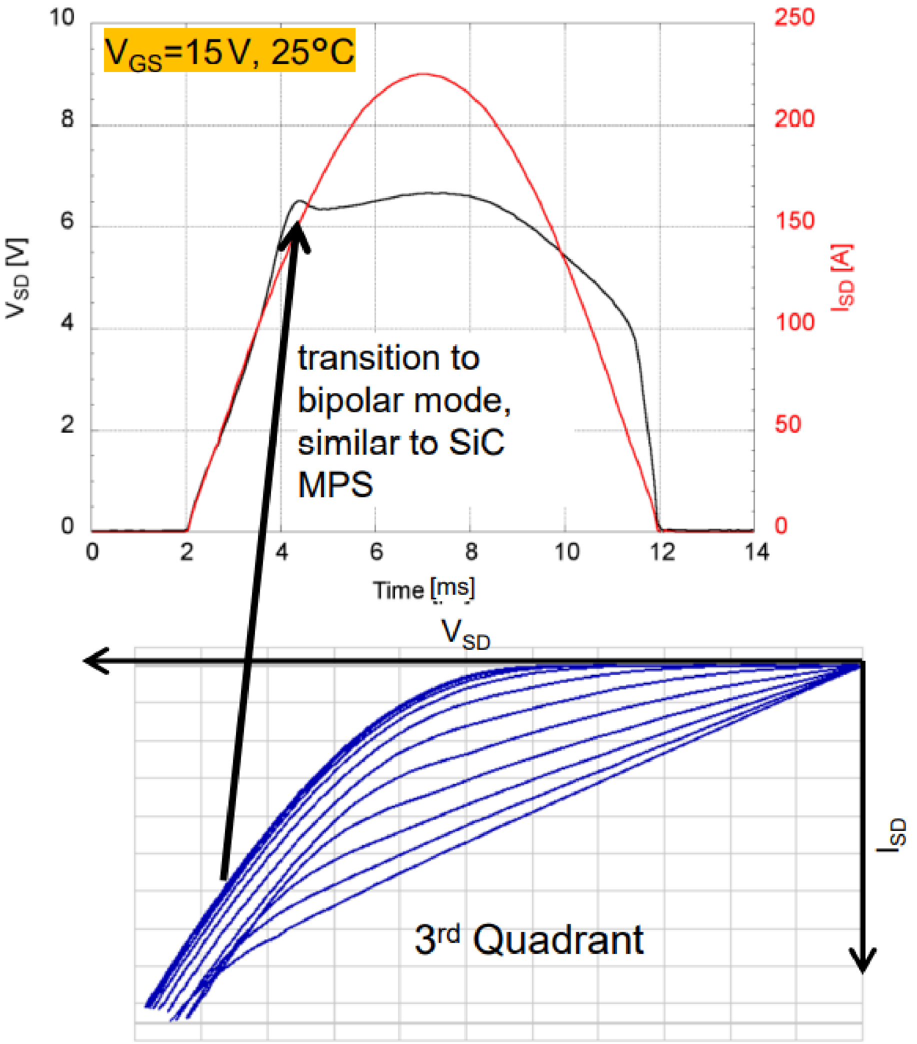
# 1200 V CoolSiC™ high current and temperature commutation robustness




**Best-in-class QRR vs. temperature reduced EMI due to recovery behavior**

# 1200 V CoolSiC™ body diode surge current behavior

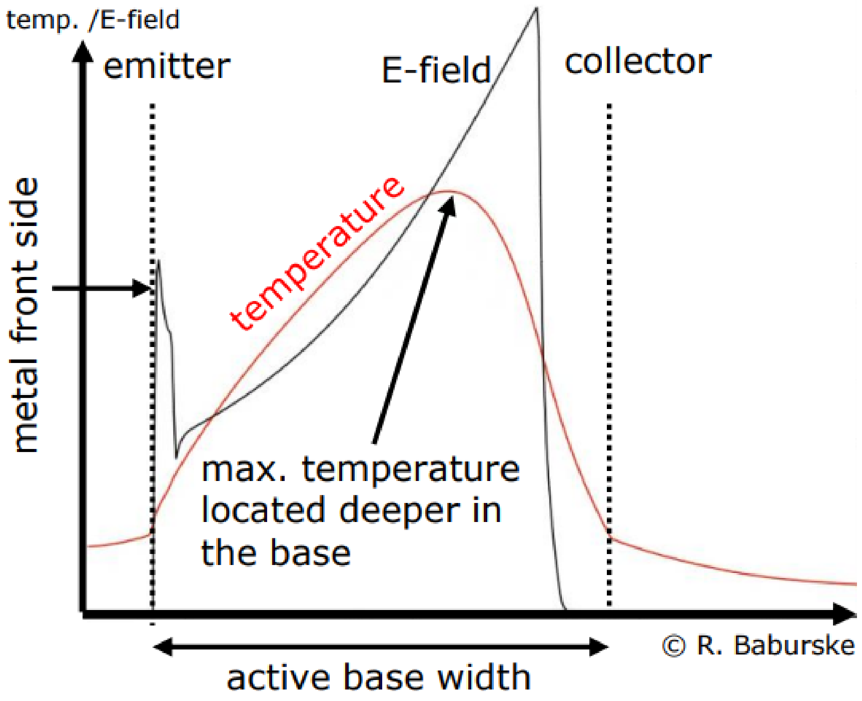


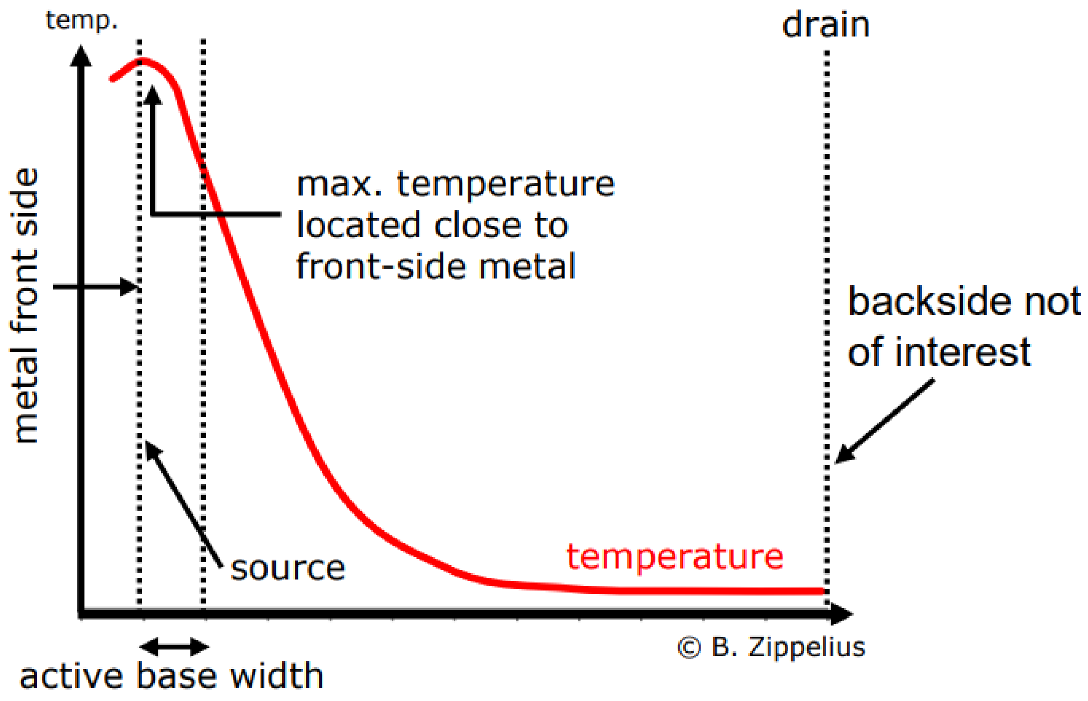

| Condition | $I_{max}$ [A], last pulse |
|---|---|
| -5 V / 25°C | 234 (10 x $I_{rat}$) |
| -5 V / 175°C | 186 |
| 15 V / 25°C | 234 |
| 15 V / 175°C | 184 |

# IGBT vs SiC MOSFET: Short-circuit temp distribution (1200 V class)

IGBT after **10µs** SC




SiC-MOSFET after **3µs** SC

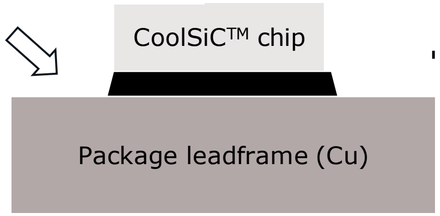


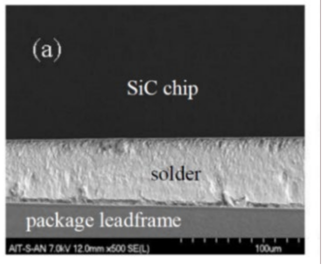

- SIC MOSFET with significantly higher temparature at front side after withstanding short-circuit event → very limited number of allowed SC events
- SI IGBT with temparature peak deep in the base (metal not much stressed)

# Significant improvement of thermal capabilities by .XT interconnection

## Standard interconnection

Standard soldering

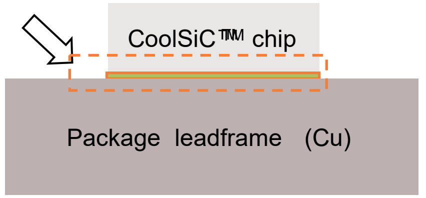


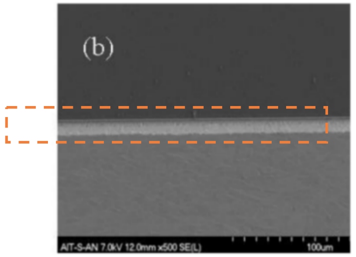




standard soldering

## .XT interconnection in TO-263-7

Diffusion soldering

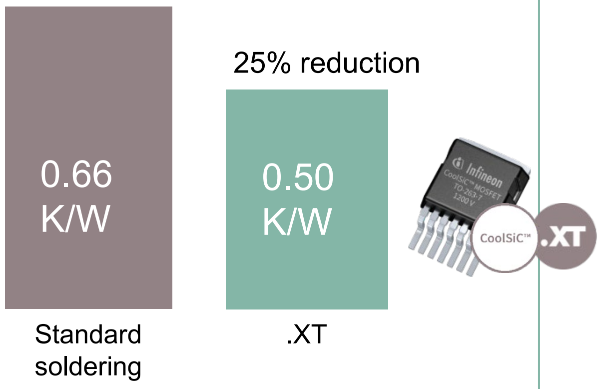


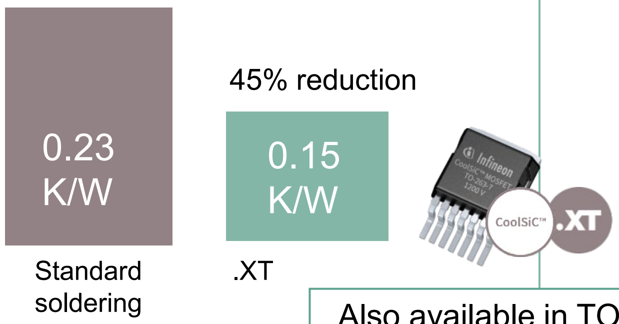

elimination of solder joint through diffusion soldering

## Thermal performance in small form factor

Max $R_{th}$




Max $Z_{th}$ @ 1 ms




Also available in TO-247 and modules

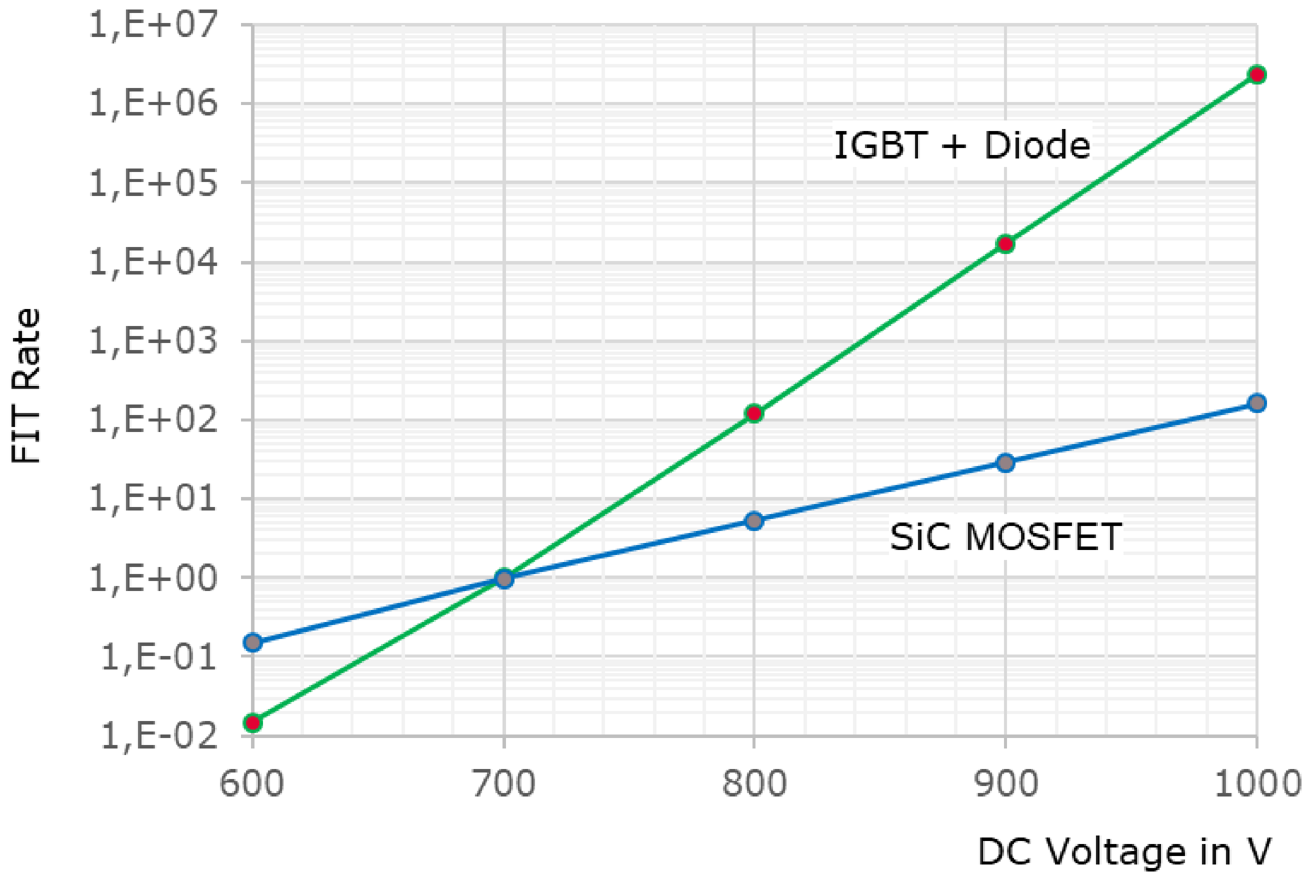
# Cosmic ray and SiC: Impact on real designs and difference from Si

SiC MOSFET: **smaller active area** than Si IGBT/diode (same current)

SiC MOSFET: **no need of free-wheeling diode** (which contributes to CR FIT)

Si FIT rate: **larger increase with rising $T_j$** (compared to a SiC MOSFET)

**Graph represents typical CR FIT values for a 200 A Si- and SiC-based half-bridge at 25ºC and sea level**



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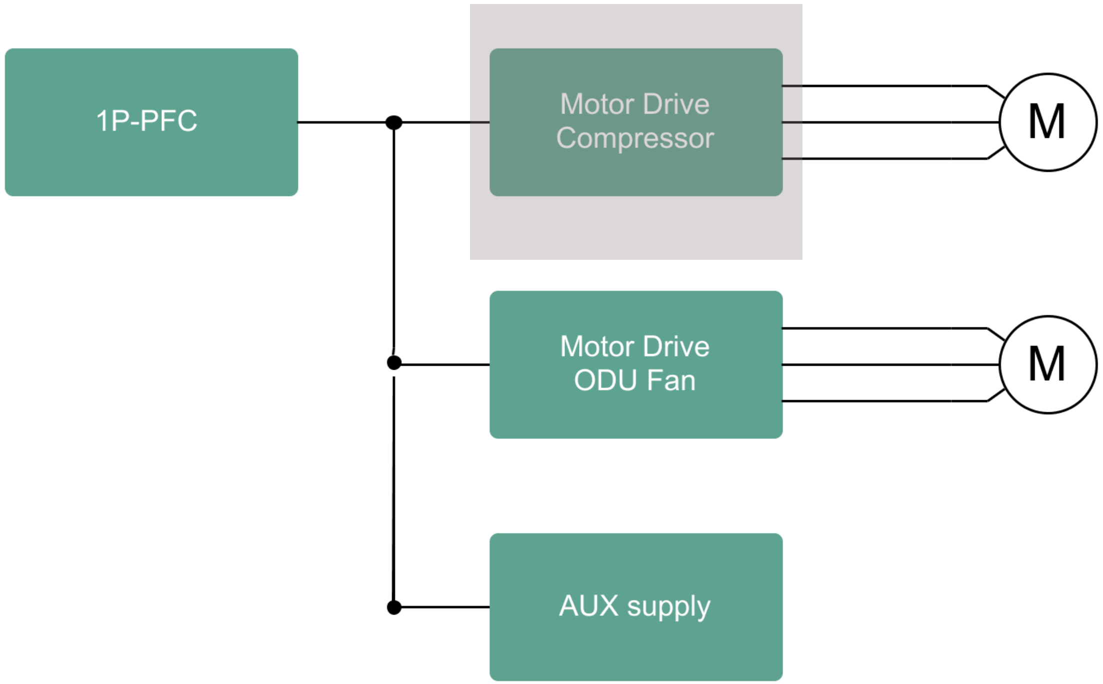
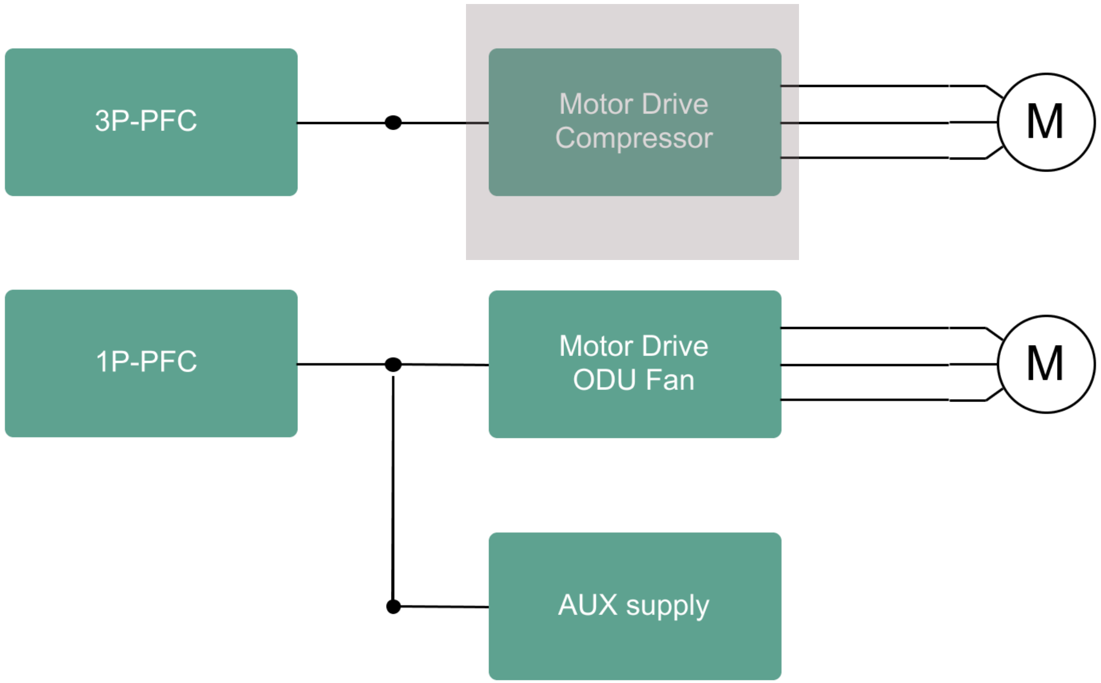
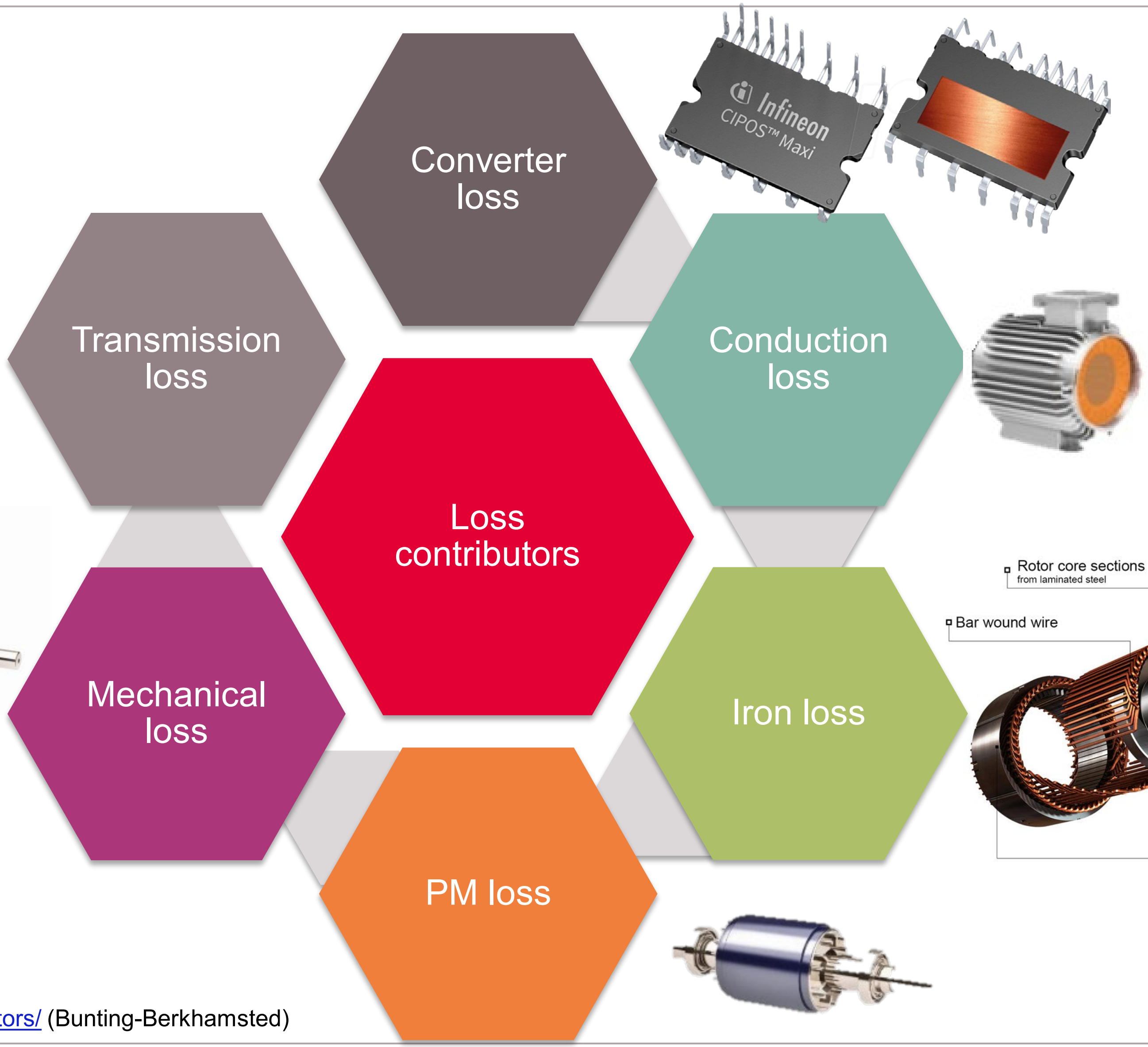
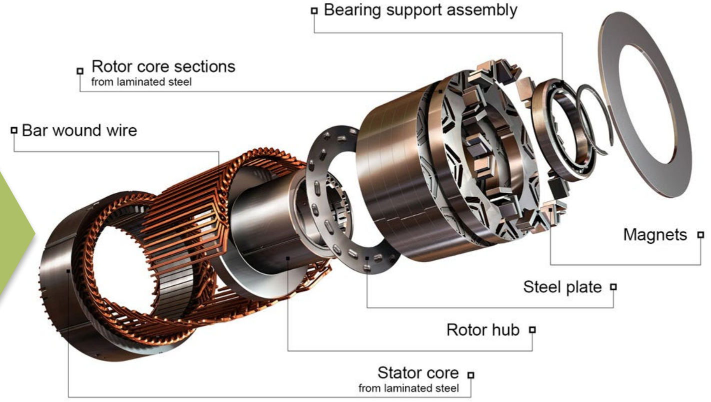
# Simplified heat pump power block diagram



# System loss contributors



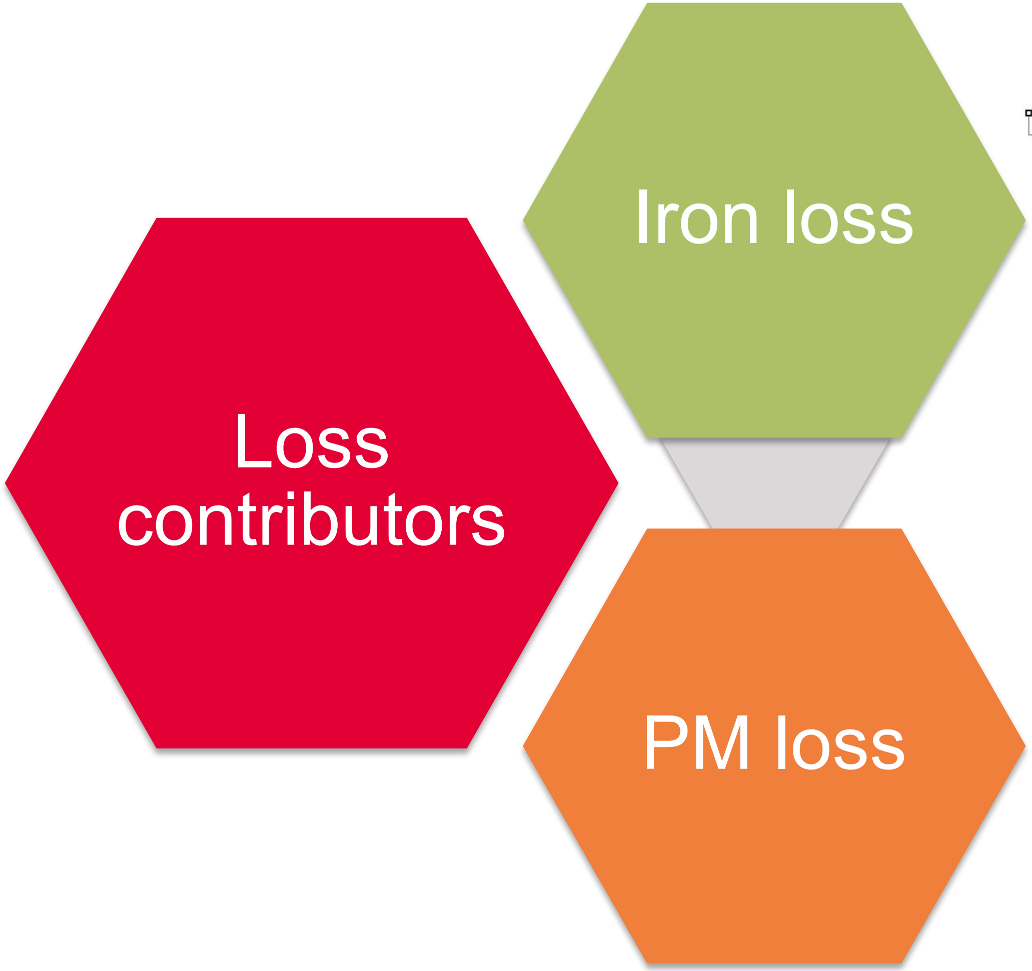

**Source motor images:**
https://media.gm.com/ (General Motors)
https://www.bunting-berkhamsted.com/industries/motors/ (Bunting-Berkhamsted)

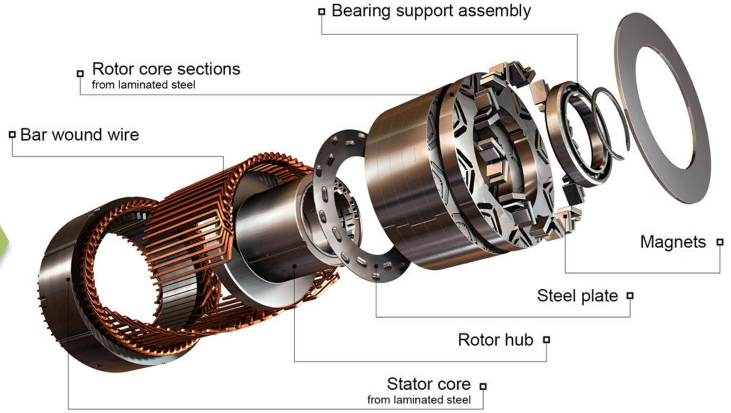
# System loss contributors

Core (iron) and permanent magnet losses depend on frequency (motor rotational speed) and flux density of the machine.

They are constituted off:

- Eddy current losses
- Hysteresis losses
- Harmonics




Power electronics effect all three constituents of core and PM losses, through switching frequency, sine wave form and power density

**Source Motor Images:**
https://media.gm.com/ (General Motors)
https://www.bunting-berkhamsted.com/industries/motors/ (Bunting-Berkhamsted)

# System loss contributors

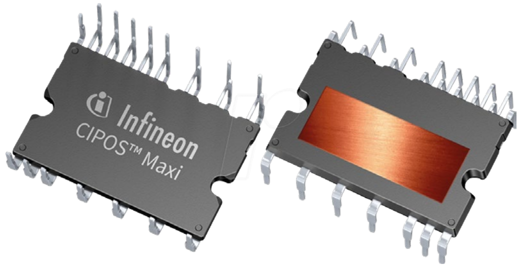
The converter losses are a direct function of the choice of power electronic technology, package, gate drive and power loop layout/design.

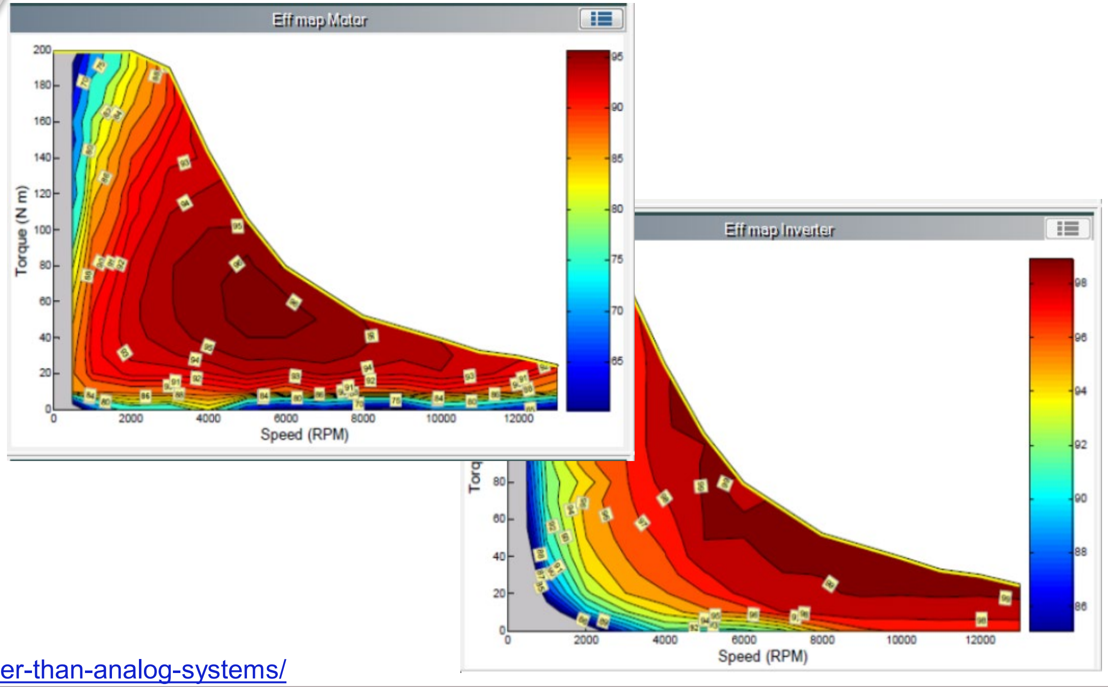
The loss contributions consist of :

- › Conduction losses
- › Switching losses
- › Gate driver losses
- › Parasitic layout losses

Converter loss

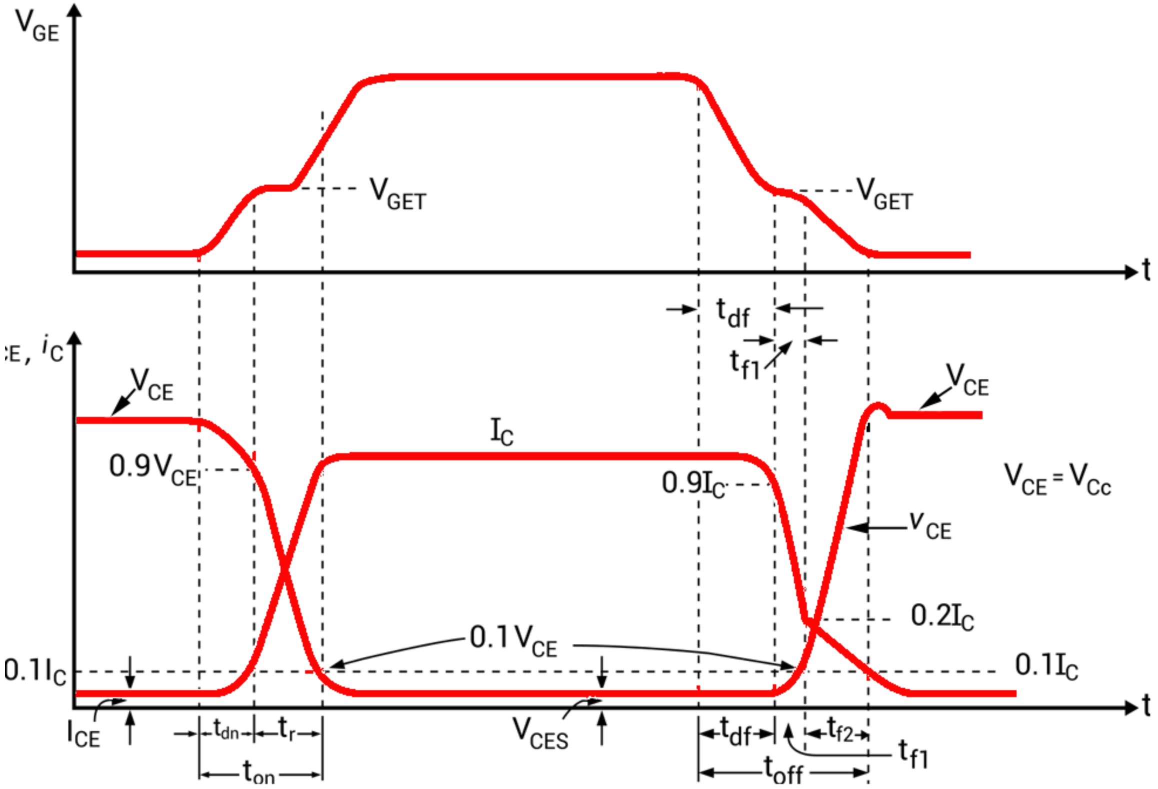
Loss contributors




**Source Efficiency Curves:**
https://www.hbm.com/en/
https://chargedevs.com/features/tech-features/hbks-digital-algorithm-can-map-ev-motor-efficiency-10-times-faster-than-analog-systems/

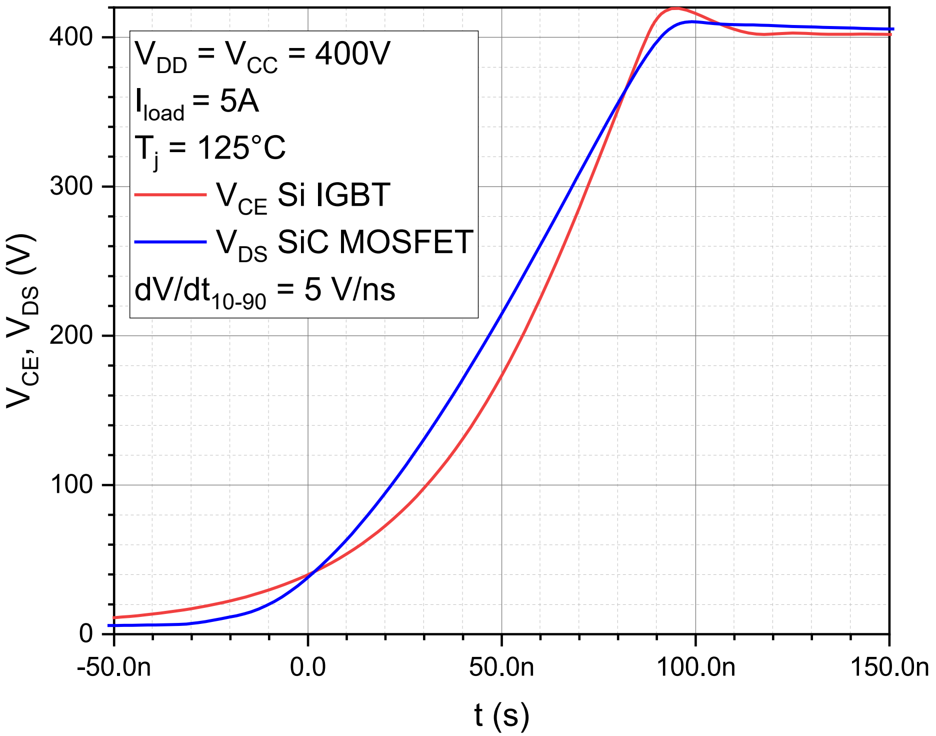
# dV/dt Misconceptions




**Source switching illustration:**IGBT, Mr. A. Johny Renoald M.E., Ph.D

Increasing dV/dt is often described as a source of:

- Damage to Motor
- EMI

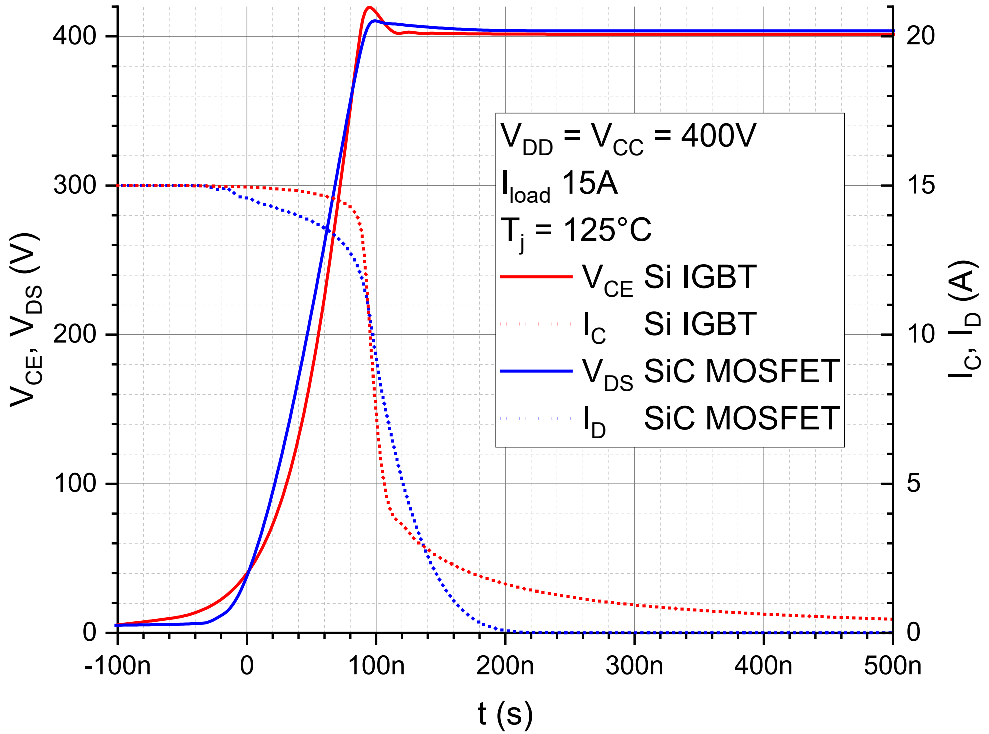



You don’t need to increase dV/dt in order to achieve system benefits

- Improved sin quality
- Lower EMI
- Losses etc…

But, with SiC, you could!

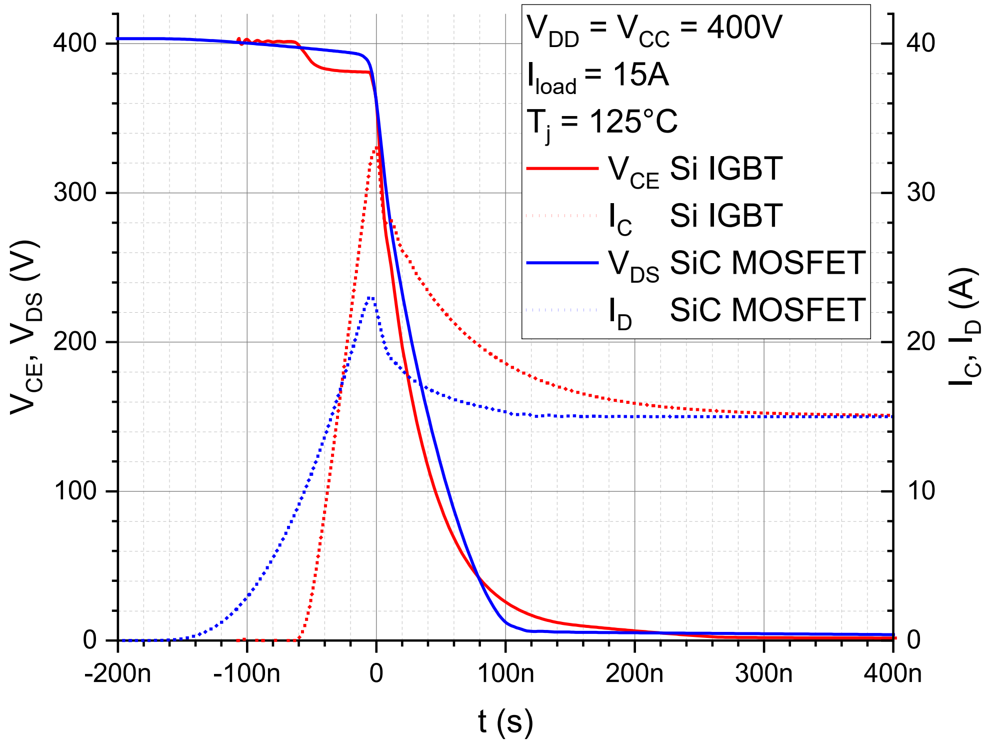
# Simulated switching curves – Turn-off




IGBT and SiC MOSFET half-bridge simulated turn-off curves with similar dV/dt (10-90%) of 5V/ns

- IGBT shows accelerated dV/dt towards higher voltage
  - Increased HF content in EMI spectrum
  - Larger overshoot under similar parasitic conditions
- MOSFET voltage transition rather smooth
- IGBT losses increased due to tail current
- No tail current in SiC MOSFET

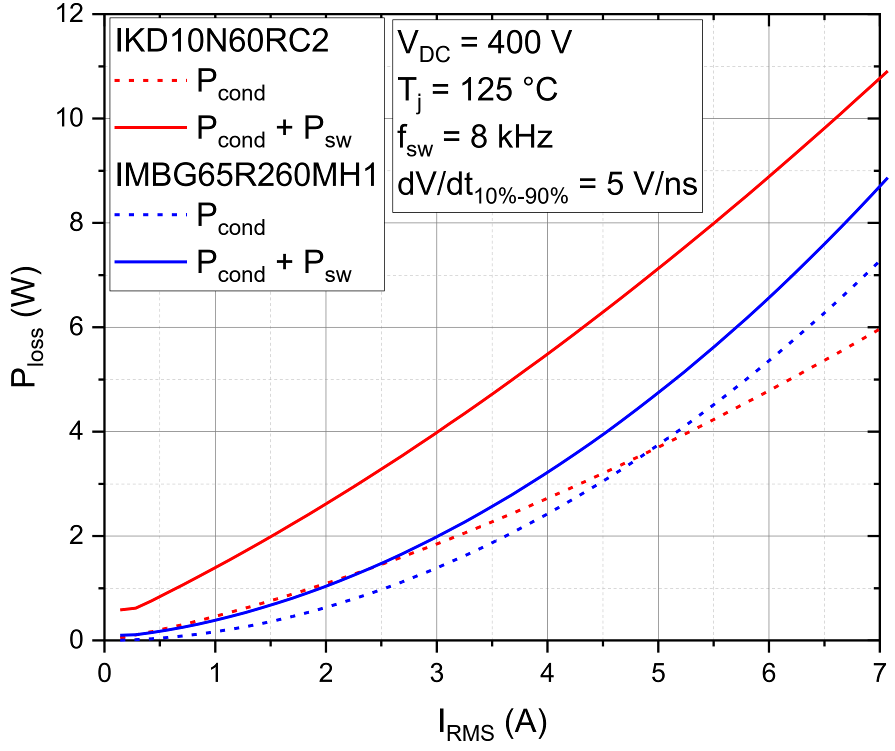
# Simulated switching curves – Turn-on

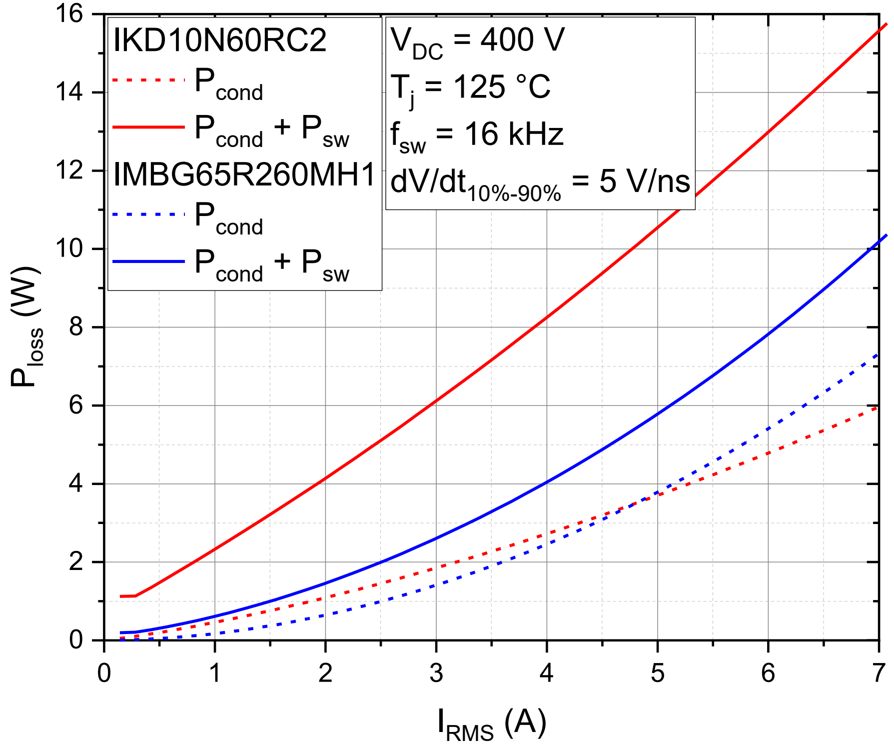



IGBT and SiC MOSFET half-bridge simulated turn-on curves with similar dV/dt (90-10%) of 5V/ns

- IGBT shows higher current peak due to diode reverse recovery and higher $C_{OSS}$
- IGBT reverse recovery current decays slowly and adds to the turn-on losses
- SiC MOSFET shows slower current slope for speed control

# Loss simulations – IGBT vs. SiC



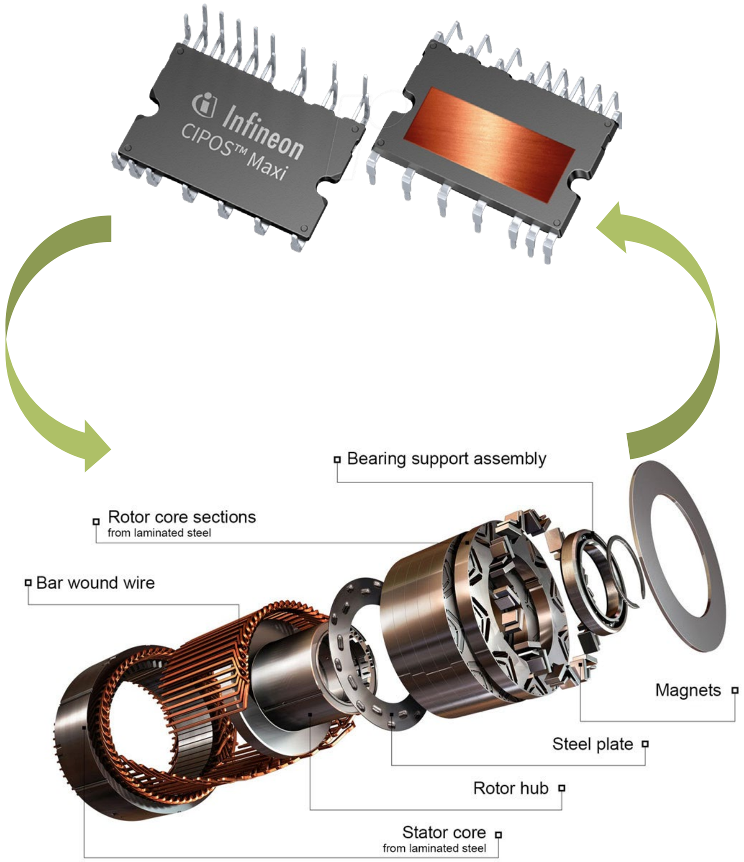




Losses per switch in a half-bridge leg under sinusoidal current assumption:

- IKD10N60RC2 and IMBG65R260MH1 show similar conduction losses at ~5A RMS current
- Switching losses of IKD10N60RC2 are significantly higher than those of IMBG65R260MH1
- Selecting the right switch for an application requires looking into all loss mechanisms

# How the semiconductor impacts the motor

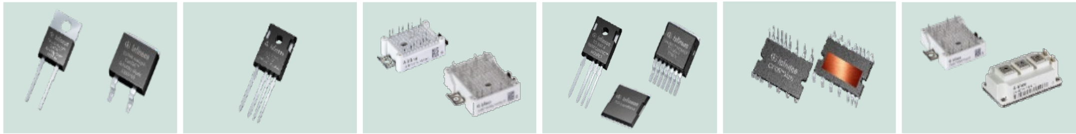
| | |
|---|---|
| Motion control | › Increased loop bandwidth<br>– Faster reaction times<br>– Higher fundamental frequency<br>› Increased loop precision<br>– Reduced distortions on fundamental signal |
| System efficiency | › Higher switching frequency<br>– Reduced eddy and hysteresis losses<br>– Reduced copper losses<br>› Reduced distortions on fundamental signal<br>– Reduced eddy and hysteresis losses<br>– Reduced copper losses<br>› Reduced inverter losses |
| Motor improvement | › Higher fundamental frequency<br>– Higher pole count motors for core loss reduction<br>– Higher RPM for gearbox / belt drive mitigation<br>› Cleaner switching edges reduce earth fault currents and EMI<br>› Reduced core and copper losses<br>– higher current → higher torque → gearbox / belt drive mitigation<br>– Weight and size reduction options → size, air resistance etc |




**Source Motor Images:**
https://media.gm.com/ (General Motors)

# Table of contents

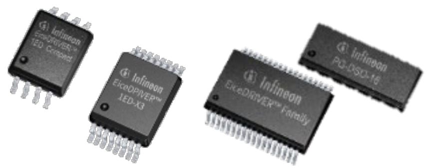
# Design degrees of freedom for the system



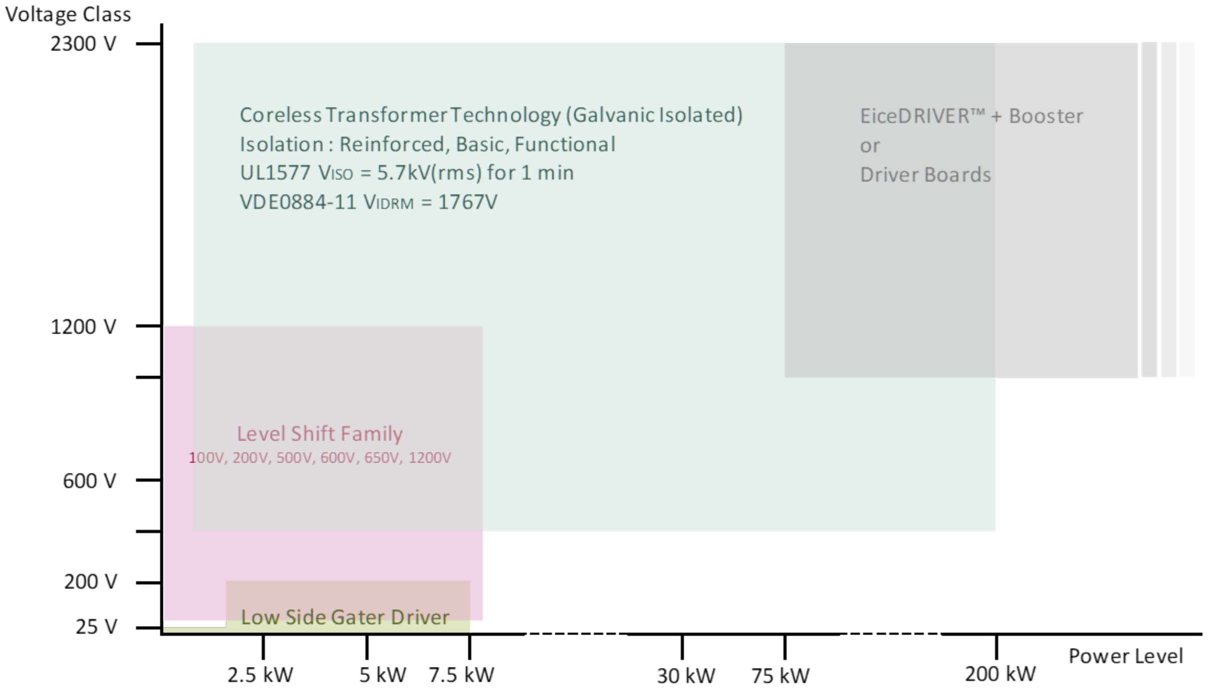
| voltages / package options | Industrial: CoolSiC™ Diode – Discrete | CoolSiC™ Hybrid – Discrete | CoolSiC™ Hybrid – Module | CoolSiC™ MOSFET – Discrete | CoolSiC™ MOSFET – IPM | CoolSiC™ MOSFET – Module |
|---|---|---|---|---|---|---|
| **600 V** | mass production | | | | | |
| **650 V** | mass production | mass production | mass production | mass production | | |
| **750 V** | | | | coming soon | | |
| **1200 V** | mass production | | mass production | mass production | mass production | mass production |
| **1700 V** | | | | mass production | | |
| **2000 V** | coming soon | | | coming soon | | mass production / coming soon |

mass production | coming soon | **Continuous extension of portfolio**

Status October 2022

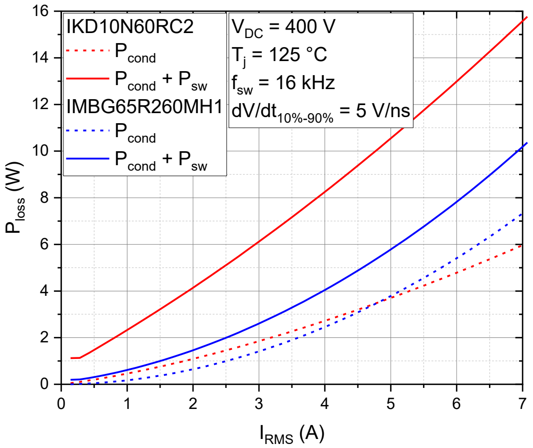


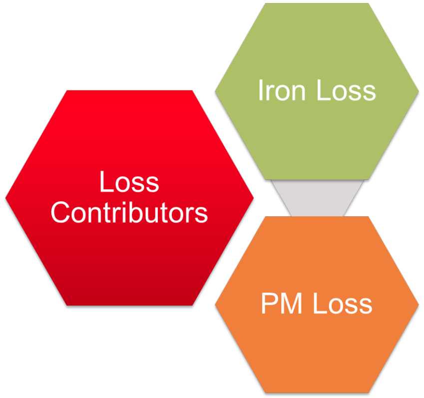
Complement the vast portfolio of CoolSiC™ MOSFETs with the EiceDRIVER™ gate driver ICs.



# Degrees of freedom

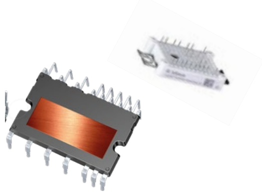
## Technology

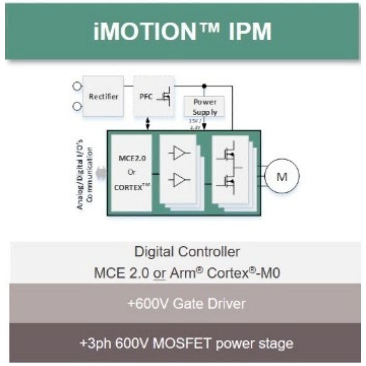


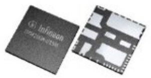




## Integration complexity

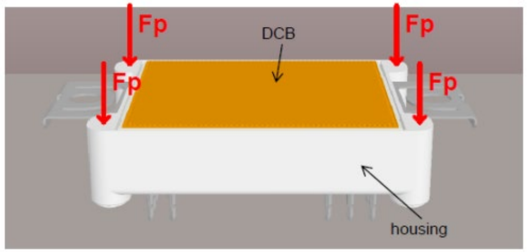
Modules Enabling Complex Topologies, IPM with Integrated Gate drivers, and even modules with µC+driver+power stage



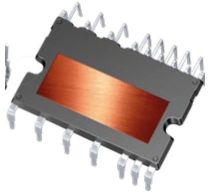


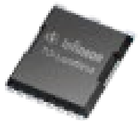



## Assembly

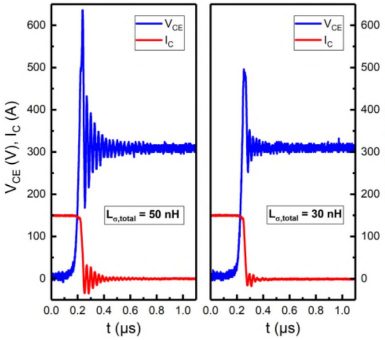



Utilize the package and footprint that suites your assembly and thermal design needs…

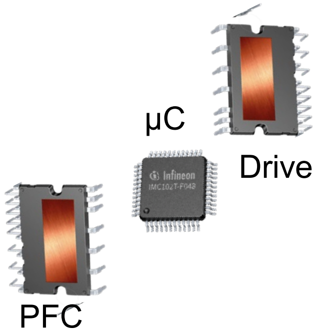




## Layout




Thermal degrees of freedom
Parasitic
Power Density…

# The new Villach 300-mm module will add significant capacity for power semiconductors

SiC — Secured manufacturing & supply

Press Release: Link, 17th February 2022


## Key criteria for site selection

- Economies of scale
- Time to revenue
- Geographic diversification

| | |
|---|---|
| Building space | ~60,000 m² |
| Total frontend investment | > 1.6bn EUR over 6 years |
| Revenue potential | > 2bn EUR per year |
| Start of construction | Early 2019 |
| Ready for equipment | Early 2021 |
| Start of production | Beginning of August 2021 |
| Technologies | IGBT and MOSFET for all end markets |

# Expansion of SiC and GaN capacity follows our long-term manufacturing strategy

SiC Secured manufacturing & supply

Press Release: Link, 17th February 2022

## Rationale

- Seize structural growth opportunities linked to electrification
- Prepare manufacturing cluster for acceleration of WBG
- Create higher resilience of WBG supply by further expanding capacities with Kulim 3 and in Villach
- Leverage economies of scale

| | |
|---|---|
| Total frontend investment | >2bn EUR |
| Revenue potential | ~2bn EUR per year |
| Groundbreaking | January 2022 |
| Start of construction | June 2022 |
| Ready for equipment | Summer 2024 |
| First volumes out | Second half of calendar year 2024 |

# Multiple supply sources along with capacity invest secure long-term success and high-volume production

Secured manufacturing & supply

**Global multi-sourcing strategy for SiC wafers and boules in place**

**Acquisition of SILTECTRA™ to double wafer usage**

**Invest in in-house capacity in Villach and Kulim**

## Supply

- "Cree, Inc. Announces Long-Term Silicon Carbide Wafer Supply Agreement with Infineon“ (26 February 2018; Go to Announcement)
- “Infineon expands supply base for silicon carbide with GT Advanced Technologies” (9 November 2020; Go to Announcement)
- “Infineon increases supply security for silicon carbide by expanding the supplier base” (6 May 2021; Go to Announcement)
- Infineon expands supplier base for silicon carbide wafers / Supply agreement signed with US-based II-VI Incorporated (23 Aug 2022, Go to Announcement)

## SILTECTRA™

- SILTECTRA™ has developed a wafer splitting technology, called Cold Split, which allows to precisely separate crystal material with minimal material losses especially compared to sawing (12 November 2018, Go to Announcement)

## In-house capacity

- Expansion of SiC and GaN capacity in Villach and Kulim
- Villach ramping up, Kulim construction started
- First volumes out of Kulim expected EO CY24

# Table of contents

# Summary

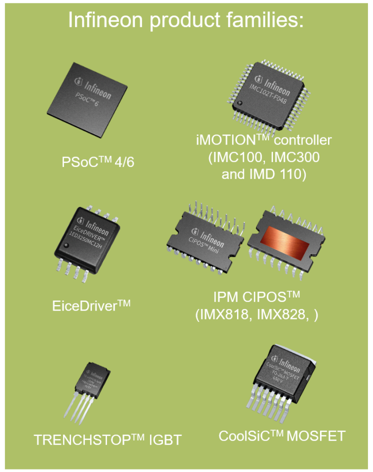
- Infineon is the semiconductor system solution provider of choice for a greener future with heat pumps
- We support our partners in finding designing in the best solution for their system
- We offer best-in-class semiconductors in a broad range of packages
- State of the art gate drivers, microcontrollers and software solutions
- From supply chain to system solution Infineon is the best partner for your applications
- Together towards a carbon neutral future

- For more information, please go to our website:

[www.infineon.com/heat-pump](www.infineon.com/heat-pump)

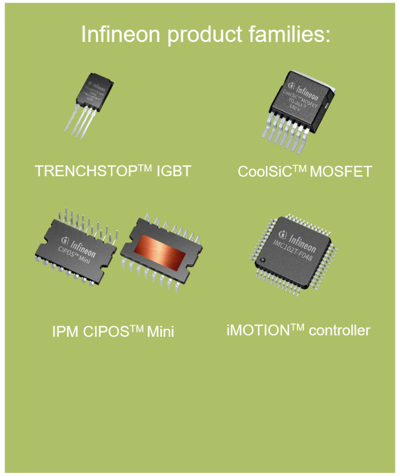
Infineon product according segmentation for compressor inverter

| Power consumption compressor | MCU | Gate driver | Power switch |
|---|---|---|---|
| low < 5 kW | PSoC™ 6/ XMC™ | EiceDRIVER™ | Si IGBT/ SiC MOSFET |
| | iMOTION™ driver (IMD110) | | Si IGBT/ SiC MOSFET |
| | iMOTION™ controller (IMC 100 and 300) | CIPOS™ IPM | |
| | PSoC™/ XMC™ | EiceDRIVER™ | EasyPIM™ |
| | iMOTION™ driver (IMD110) | | |
| high > 5 kW | PSoC™/ XMC™ | EiceDRIVER™ | Si IGBT/ SiC MOSFET |
| | iMOTION™ driver (IMD110) | | Si IGBT/ SiC MOSFET |
| | PSoC™/ XMC™ | EiceDRIVER™ | EasyPIM™ |
| | iMOTION™ driver (IMD110) | | |




Infineon solution with product for PFC

| Current phase | MCU | Gate driver | Power switch |
|---|---|---|---|
| 1 N/ 230 V/ 50 Hz | PSoC™/ XMC™ | EiceDRIVER™ | Si IGBT/ SiC MOSFET |
| CCM Interleaved or Totem-pole PFC | PSoC™/ XMC™ | CIPOS™ Mini IPM | |
| | iMOTION™ controller | CIPOS™ Mini IPM | |
| | iMOTION™ driver | | EasyPIM™ |
| 3 N/ 400 V/ 50 Hz | PSoC™/ XMC™ | EiceDRIVER™ | Si IGBT/ SiC MOSFET |
| CCM Interleaved, Sixpack and Vienna Rectifier | PSoC™/ XMC™ | EiceDRIVER™ | EasyPack™ |
| | iMOTION™ driver | | |
| | iMOTION™ driver | | CIPOS™ Maxi IPM |



Part of your life. Part of tomorrow.