Power conversion switch technology: the who, when , where and why of using Si, SiC and GaN transistors

Peter Friedrichs,

Infineon Technologies AG

Content

1. What drives next generation power devices ?

2. Playground for Wide band gap technologies today and tomorrow

3. Is Silicon for power already at the end ?

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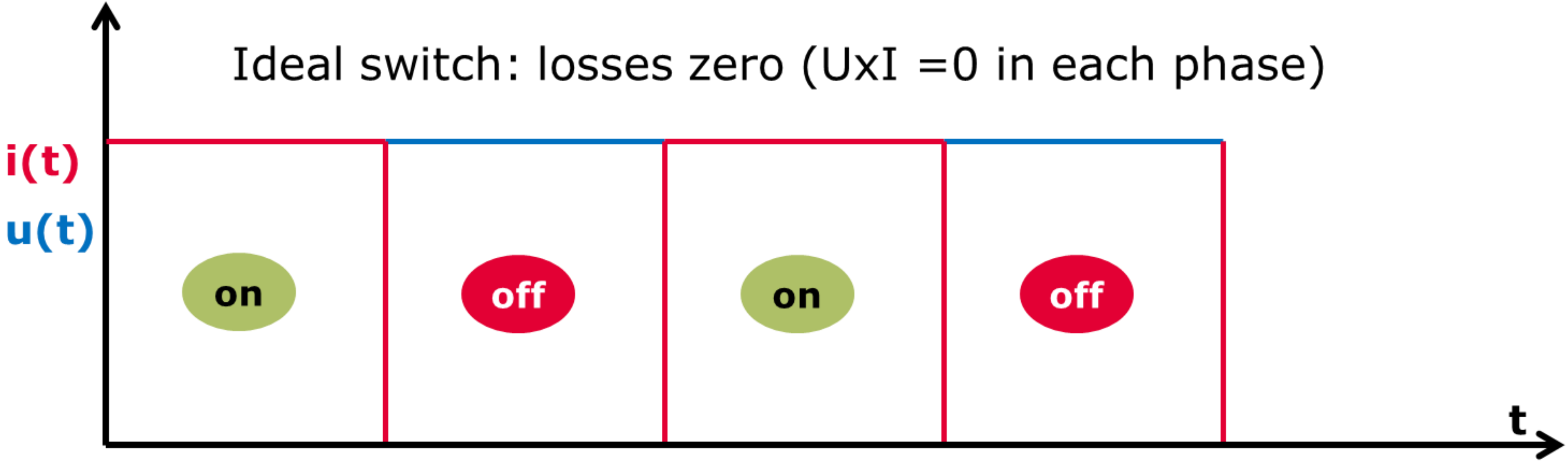
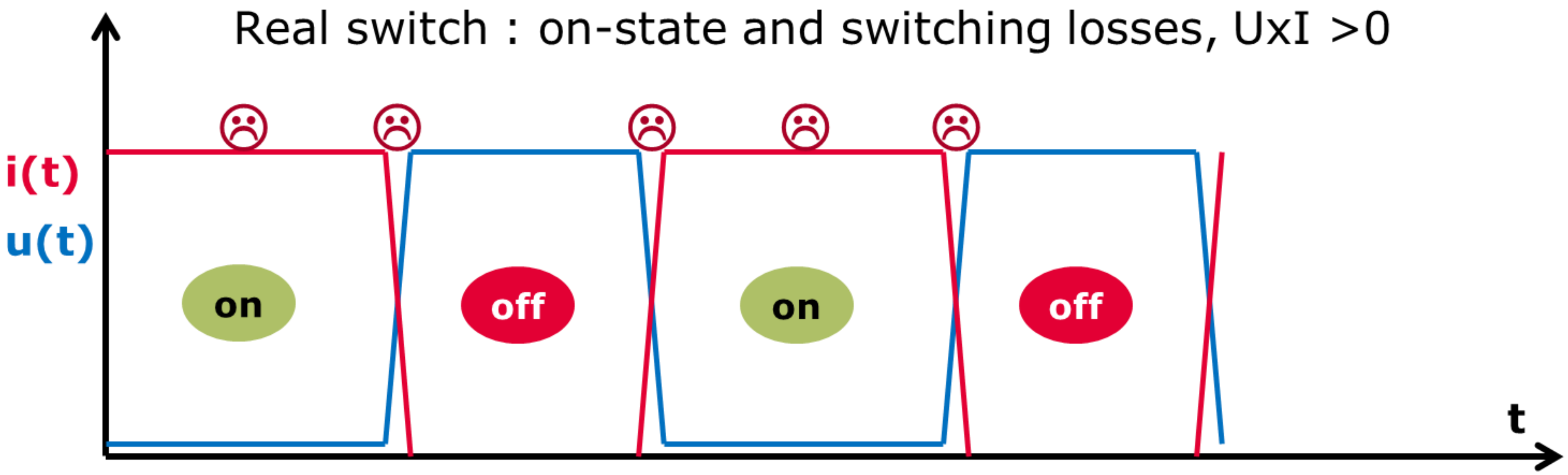
Power conversion by switching in a nutshell – avoid losses in switch elements since those just generate heat



Power conversion by switching in a nutshell – avoid losses in switch elements since those just generate heat

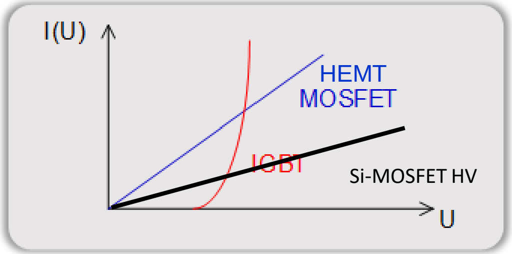


Power conversion by solid state switches – origin of losses

Loss origin – conduction

resistance (MOSFET, HEMT, IGBT)

knee voltage (IGBT)

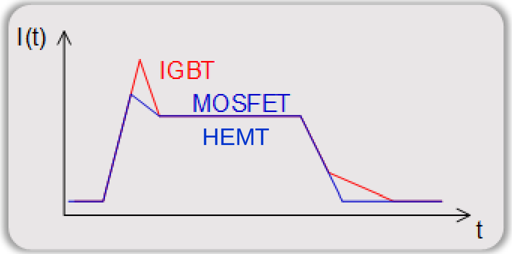


Loss origin – switching

C- charging (MOSFET, HEMT, IGBT)

minority carrier dynamics (IGBT)

minority carrier dynamics (pn-diode)



MOSFET/HEMT normally preferred since losses due to knee voltage or minority carriers not in place, but in case of silicon significant penalty by increasing conduction losses

Wide bandgap characteristics offer advantages for power electronics

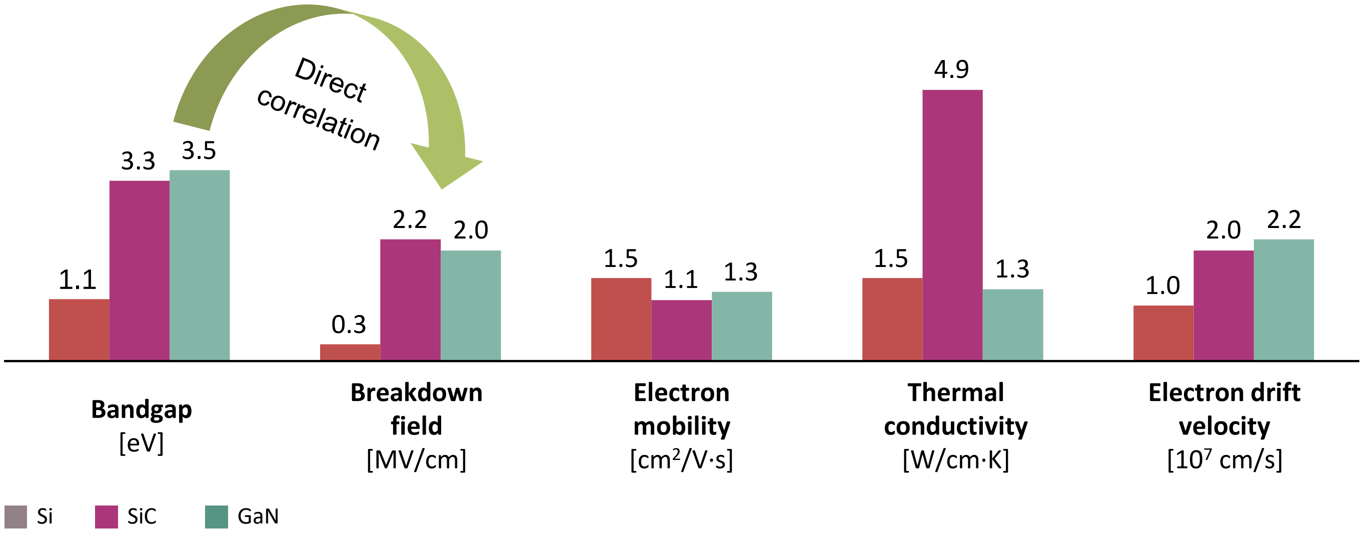
Extended power density

Higher voltage operation

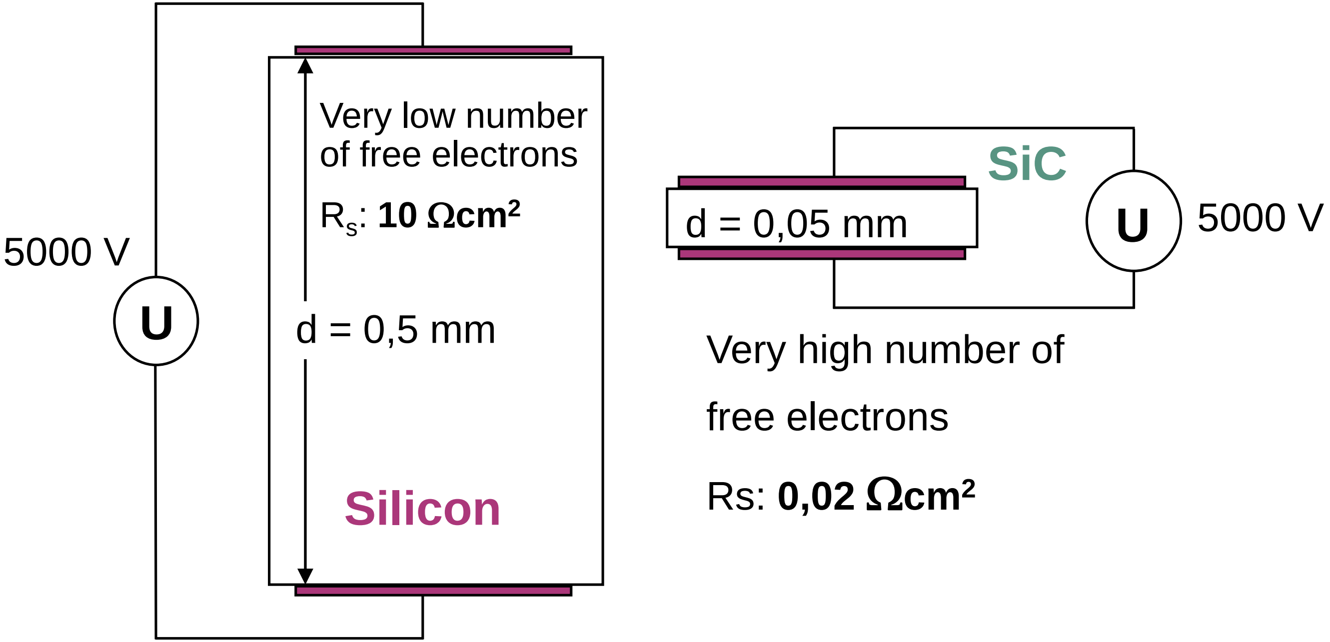
Higher frequency switching

Thinner active layers

Improved head dissipation



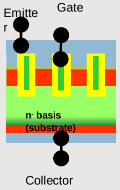
WBG based semiconductors can withstand higher internal electric fields – what does it mean ? Example: 5kV power device



Infineon will complement each of its leading edge silicon solutions by a wide bandgap technology!

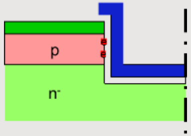
>1000V

TRENCHSTOP™ to CoolSiC™



Si
IGBT

SiC
MOSFET

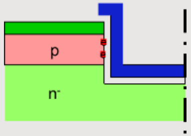


600..900V

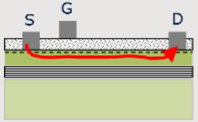
CoolMOS™ to CoolGaN™ and CoolSiC™

Si
Superjunction

SiC
MOSFET

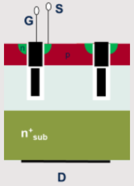


GaN
HV e-mode lateral HEMT



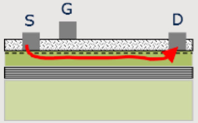
<400V

OptiMOS™ to CoolGaN™



Si
Fieldplate

GaN
MV e-mode lateral HEMT



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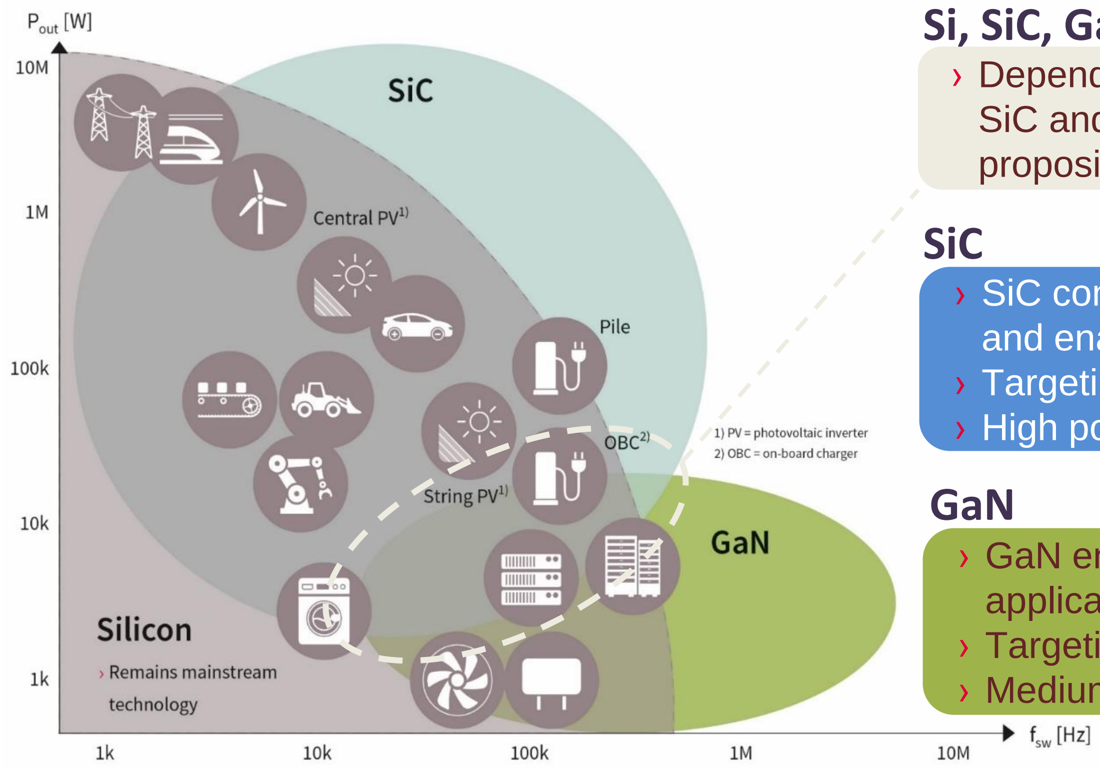
Si, SiC and GaN – positioning across various applications



Si, SiC, GaN

- Depending on application requirements Si, SiC and GaN all have a specific value proposition in the 600V/650V segment

SiC

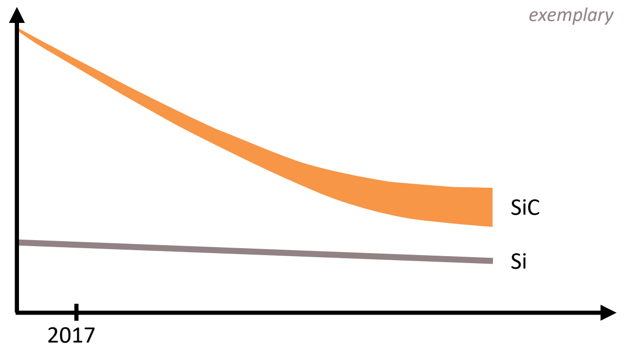
- SiC complements Si in many applications and enable new solutions
- Targeting 600V – 3.3 kV
- High power - high switching frequency

GaN

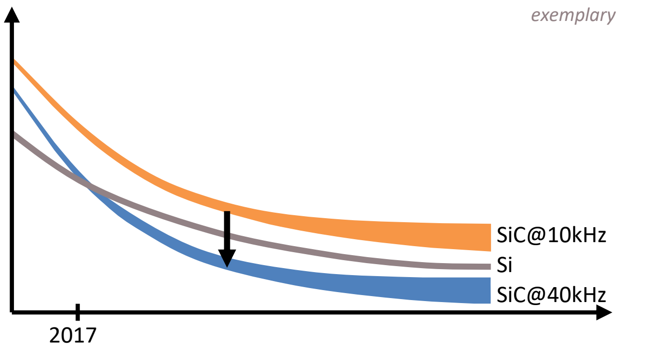
- GaN enable new horizons in power supply applications and audio fidelity
- Targeting 100V - 600V
- Medium power - highest switching frequency

System integration and energy savings will be a key lever for power electronics – example SiC situation

Chip costs

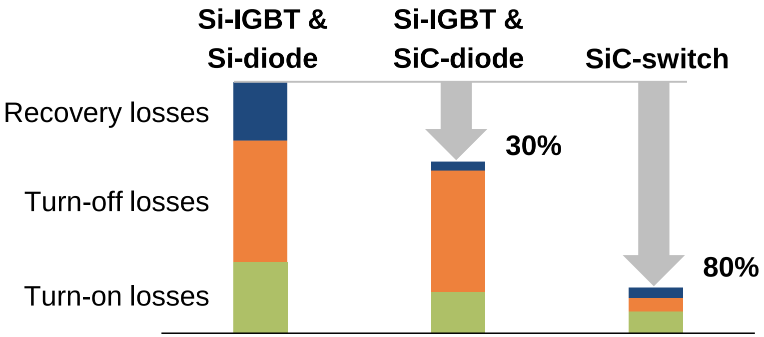


System costs



Cool SiC™

best in class
switching frequency,
conduction losses
and radically improved
efficiency



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Where are the major playgrounds for SiC devices today and what are the next big moves – tipping point model

Photovoltaic
- reduction of system cost
- reduction of system size

EV charging
- faster charging cycles

IPS
- higher efficiency,
- reduced total cost of ownership

tipping point reached

eMobility
- higher reach per charge
- more compact main inverter

Traction
- lower system cost
- higher seat capacity

Drives
- reduced system size
- reduced total cost of ownership

future tipping points

Tipping point passed in solar - Customer value proposition for PV string inverters: power density increase by 2.5

Development of Kaco String Inverters

Year 2008, 100 kW, 1129 kg, 2,12m Height
Si

Year 2011, 50 kW, 151 kg 1,36 m Height
Si

Year 2016, **50 kW**, 70 kg, 0,76 m Height
Si

Year 2018, **125 kW**, 77 kg, 0,72 m Height
SiC

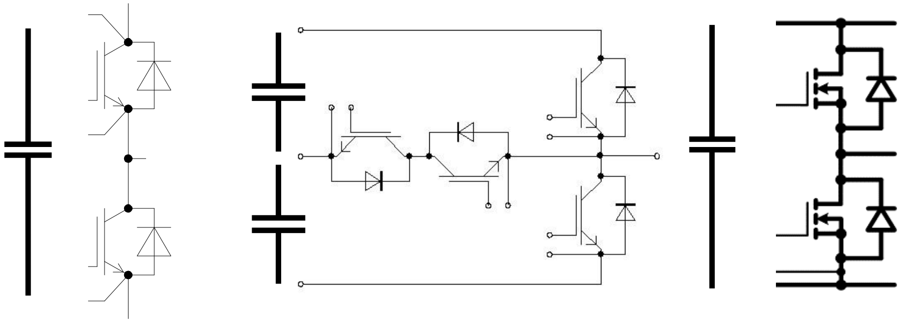
Value Proposition

- Power density increase by factor 2,5 (50kW → 125kW)
- Reduction of number of switches (5-level to 3-level) leads to reduced risk of field failures
- SiC provides less reduction in efficiency at high operating temperatures → better efficiency (99,1% vs 98,9%)

Source:
https://www.pv-magazine.de/2018/11/14/pv-magazine-top-innovation-kacos-neuer-siliziumkarbid-wechselrichter/

The next big opportunity for SiC transistors
High Power UPS Topologies

UPS



Si 2-Level	Si 3-Level NPCT	SiC 2-Level
10 Years ago	5 Years ago	In 2019
3.2% losses* at 6kHz	2.9% losses* at 8kHz	1.7% losses* at 32kHz

*% Losses of Power Semi Devices at 300kW and 400Vac

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Tipping point reached by significant cost of ownership reduction

500kWhrs x 24 hours x 365 days x 5 years =
22 million kWhrs processed power through UPS

- **Si 2-Level at 3.2% loss** = 700,000 kWhrs x 1.2 factor* = 840,000 kWhrs
  - In EU at €.10 per kWhr = **€84,000**

- **Si 3-Level at 2.9% loss** = 640,00 kW 1.2 factor* = 760,000 kWhrs
  - In EU at €.10 per kWhr = **€76,000**

- **SiC 2-Level at 1.7% loss** = 374,000 kWhrs x 1.2 factor* = 450,000 kWhrs
  - In EU at €.10 per kWhr = **€45,000**

+SiC

*1.2 factor reflects the energy used for air conditioning to extract heat from a building with UPS installed

CoolGaN™ initial target applications

Servers

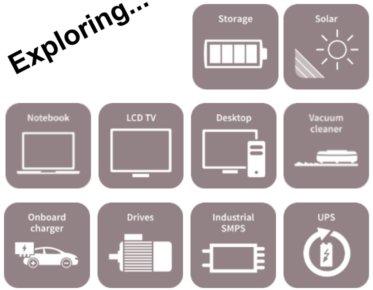
Telecom

Wireless charging

Audio

Adapters

Exploring...



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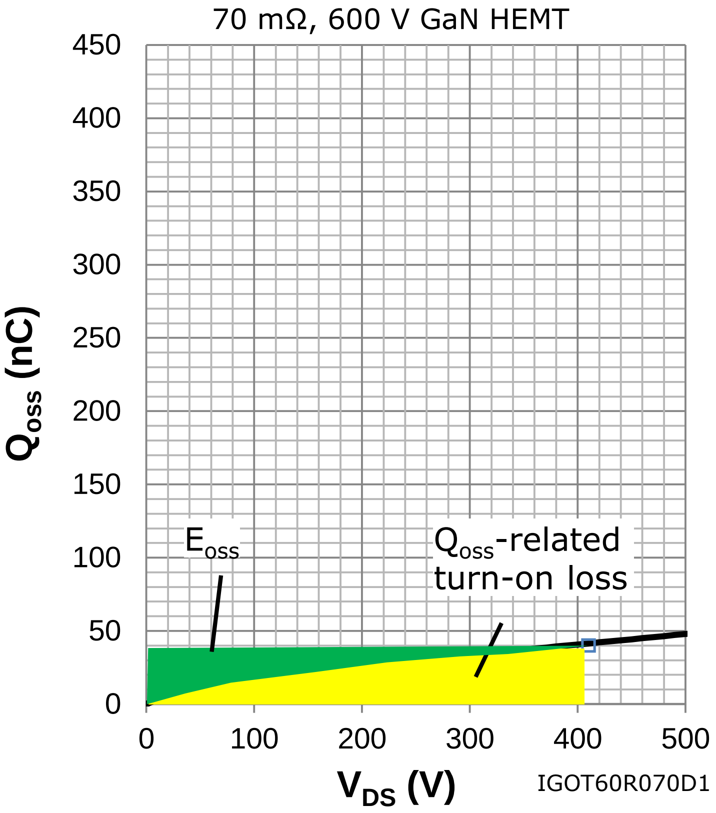
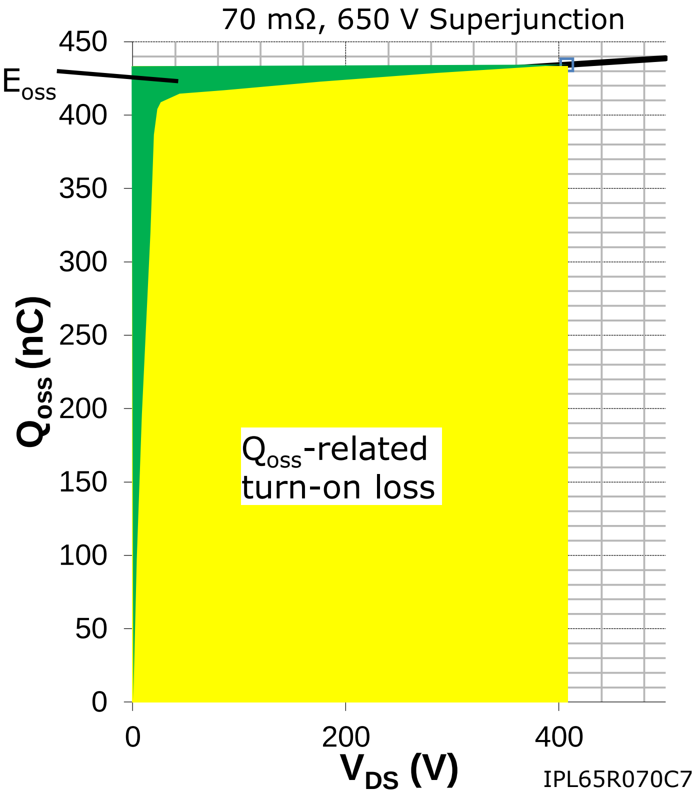
Benefit of GaN versus Superjunction MOSFETs - Q_{oss}





Feature comparison between GaN, SiC and Si SJ for power supply applications

FOM $R_{DS}ON$ x	SJ	GaN	SiC
		CoolGaN™ advantage	
Q_{RR}	High, snappy	zero	Very small
E_{OSS}	low	lower	lower
C_{OSS} shape	Non-linear	linear	linear
Q_G	high	Very low	low
Q_{OSS}	Very high	low	low
Device concept	vertical	lateral	vertical

In the 600V segment 600 V CoolGaN™ and CoolSiC™ are ideal components for Totem Pole PFC and LLC/ZVS PSFB

Simpler, HB topology

PFC — **Highest efficiency with reduced component count**

PFC — **System cost reduction**

PFC — **For single switch topologies Eoss is key CoolMOS™ is still the best choice**

Higher fsw, no penalties

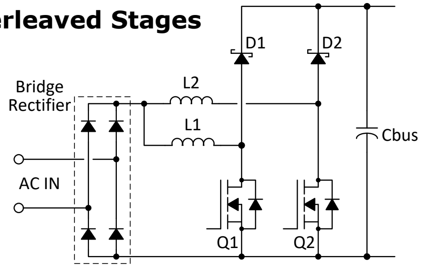
PWM — **Higher power density**

Next generation will target **multi-chip integration**

PFC – WGB enables simpler and more efficient half bridge topologies such as Totem Pole

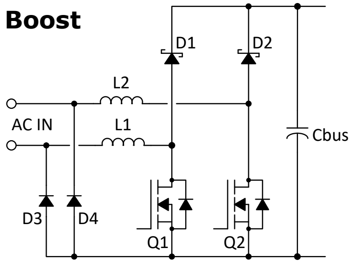
Nowadays, several high efficient topologies for CCM PFC are available. BOM costs and part count depend on efficiency targets

Interleaved Stages



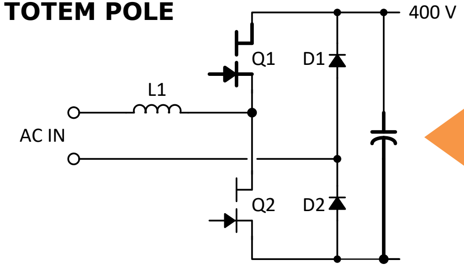
Body diode (Qrr) prevents half bridge topologies

Dual Boost



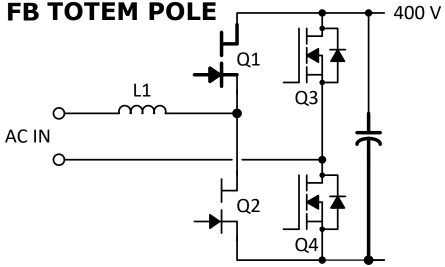
WBG technologies (GaN HEMT or SiC MOSFET) enable to use **simpler** and **cost effective** HalfBridge/**Hard switching** topologies and at the same time to achieve **higher** efficiency

HB TOTEM POLE



GaN has zero Qrr

FB TOTEM POLE



The investment in WBG has a **compelling payback** which allows to absorb very rapidly the initial higher costs of WBG switches

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IGBT’s have already enabled an impressive Power density race

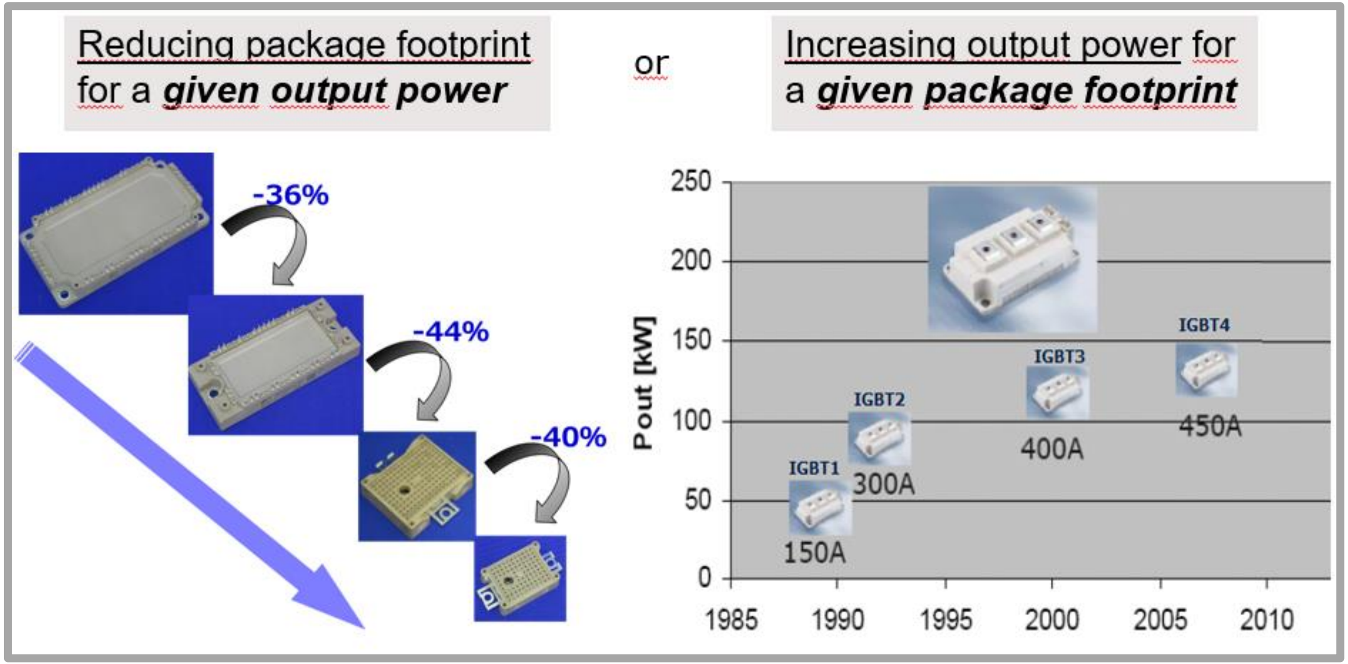

Figure out of:
N. Iwamuro et al., “IGBT History, State-of-the-Art, and Future Prospects,” *IEEE Trans. Electron Devices*, vol.64, no. 3, pp.741-752, 2017

- **was enabled by progress in**
  - IGBT cell technology
  - vertical design
  - interconnect technology
  - increased maximum junction temperature

- **and will proceed also in the future …**

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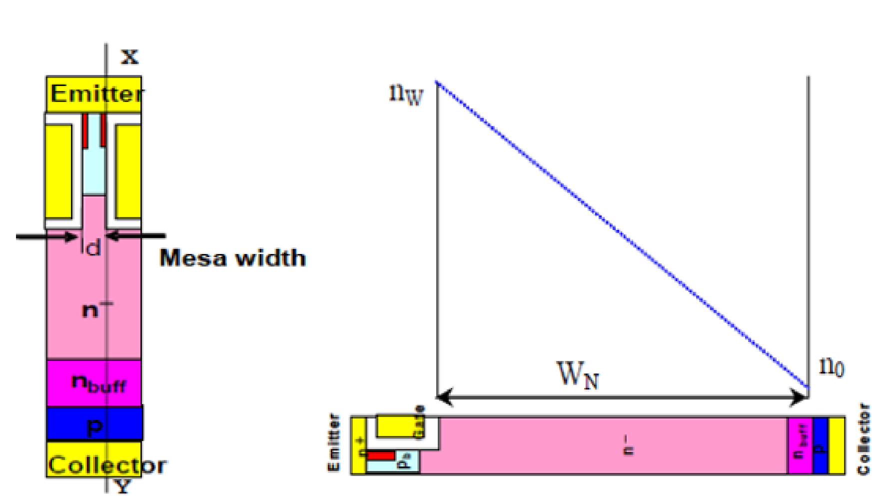
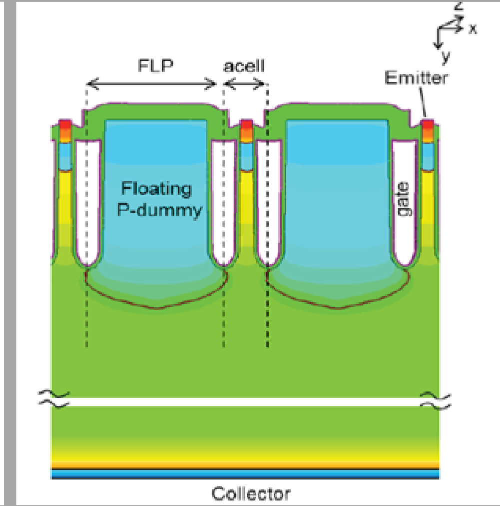
Next IGBT generation – driven by advanced cell concepts





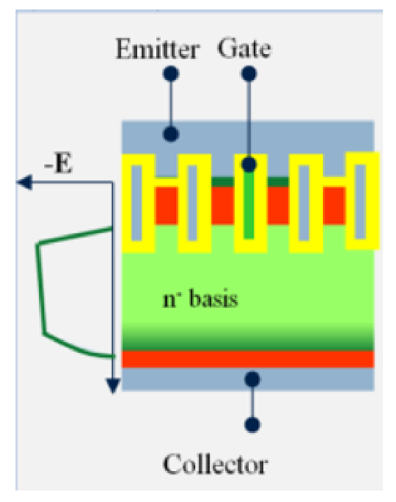


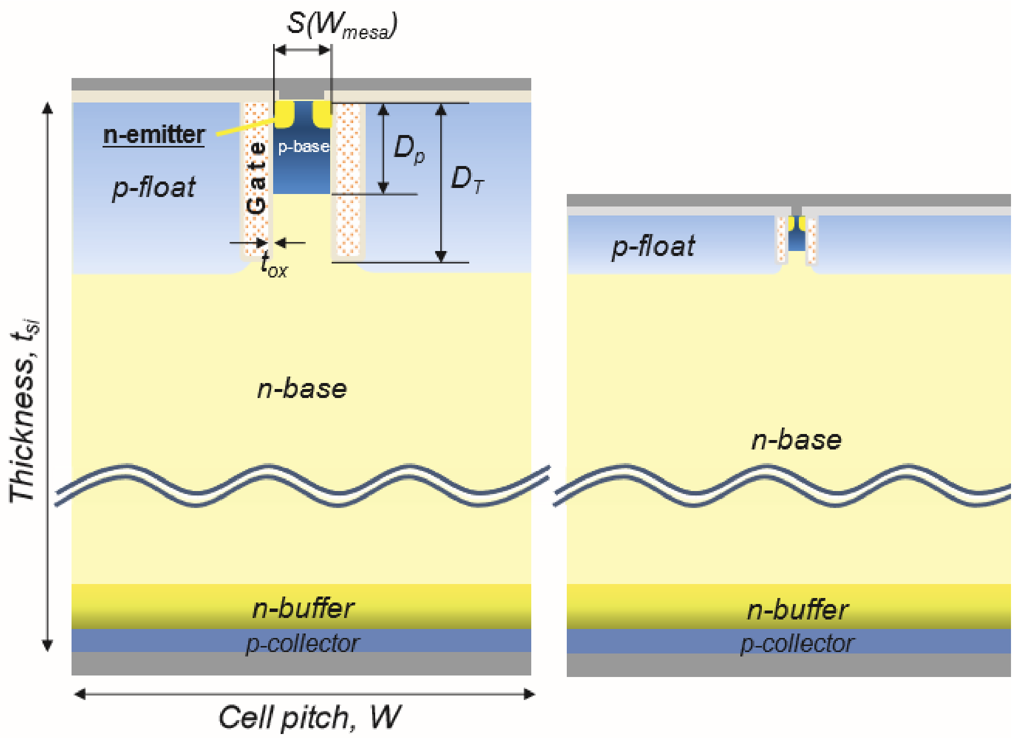
Fig. out of: A. Nakagawa, "Theoretical Investigation of Silicon Limit Characteristics of IGBTs," in *Proceedings of Int. Symp. Power Semiconductors and ICs*, pp. 5-8, 2006.

Fig. out of: K. Eikyu et al., "On the Scaling Limit of the Si-IGBTs with Very Narrow Mesa Structure," in *Proceedings of Int. Symp. Power Semiconductors and ICs*, pp. 211-214, 2016.

Fig.out of:
F. Wolter et al., "Multi-dimensional Trade-off Considerations of the 750V Micro Pattern Trench IGBT for Electric Drive Train Applications," in *Proceedings of Int. Symp. Power Semiconductors and ICs*, pp. 105 - 108, 2015..

› **Trend to investigate IGBTs with mesas in the (deep) sub-micron range:**
on state voltage < 1 V for a 1200 V IGBT seems achievable; but, reasonable switching losses, switching speed and short circuit robustness "not that easy".

Advanced gate-driving aspects, example I: “Scaled” IGBT

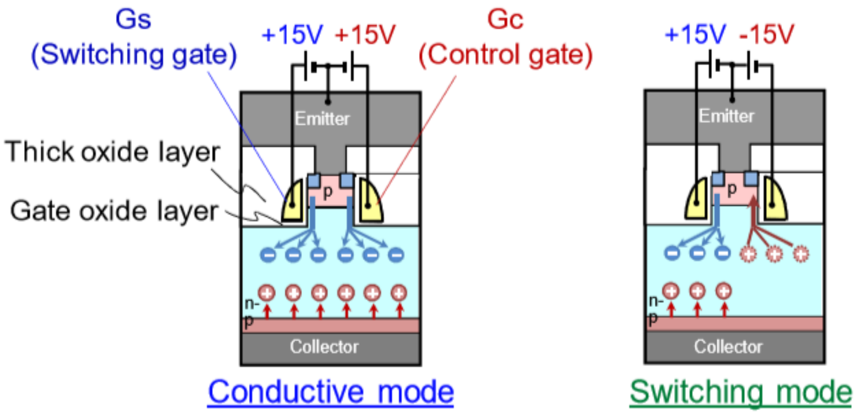


(a) k=1 (b) k=3

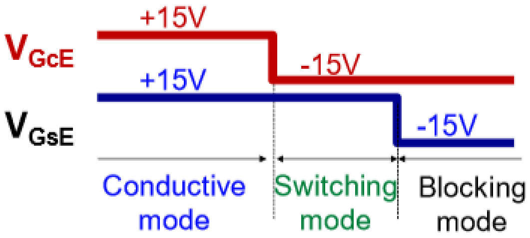
- **Trend to investigate IGBTs with lower threshold voltage and lower V_{GE_use} (e.g. 5 V instead of 15 V), very similar to GaN HEMT e.g.**
  - Potential “Pro‘s“: lower V_{CEsat}, lower gate charge, lower driving power
  - Potential „Con“: bigger influence of parasitics (e.g. parasitic turn on).

Fig. out of: T. Saraya et al., “Demonstration of 1200V Scaled IGBTs Driven by 5V Gate Voltage with Superiorly Low Switching Loss,” *IEDM*, pp.189-192, 2018.

Advanced gate-driving aspects, example II: “Dual Gate” IGBT



- **Trend to investigate IGBTs with 2 external gates**
  - Potential “Pro“: Enabling low on state voltage V_{CEsat} and low turn off losses E_{off} by decreasing the carrier plasma before turning off using the second gate
  - Potential “Con“: bigger gate-driving effort



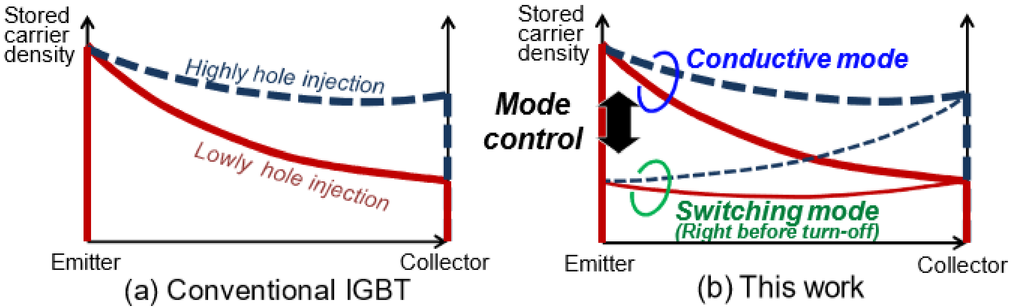
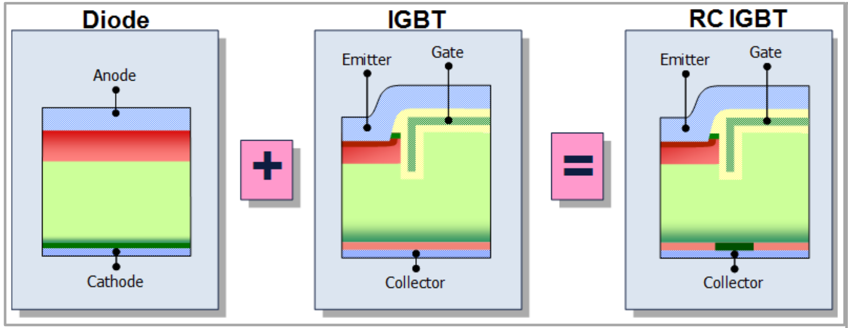
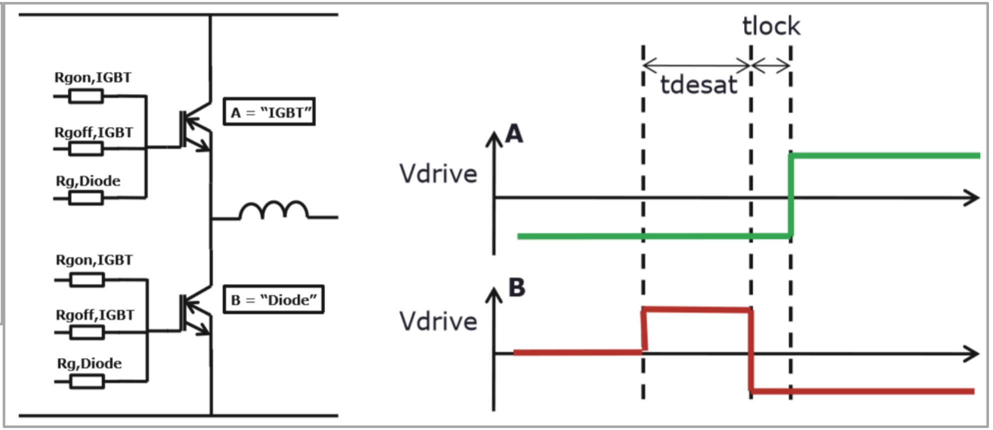


Fig. out of: T. Miyoshi et al., *“Dual side-gate HiGT breaking through the limitation of IGBT loss reduction,”* Proc. of PCIM, pp. 315-322, 2017.

Advanced gate-driving aspects, example III: “RC-(DC)” IGBT “Reverse-conducting (diode-controlled)” IGBT





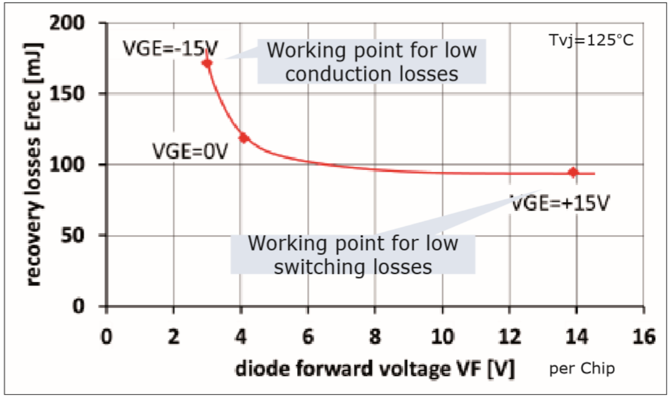
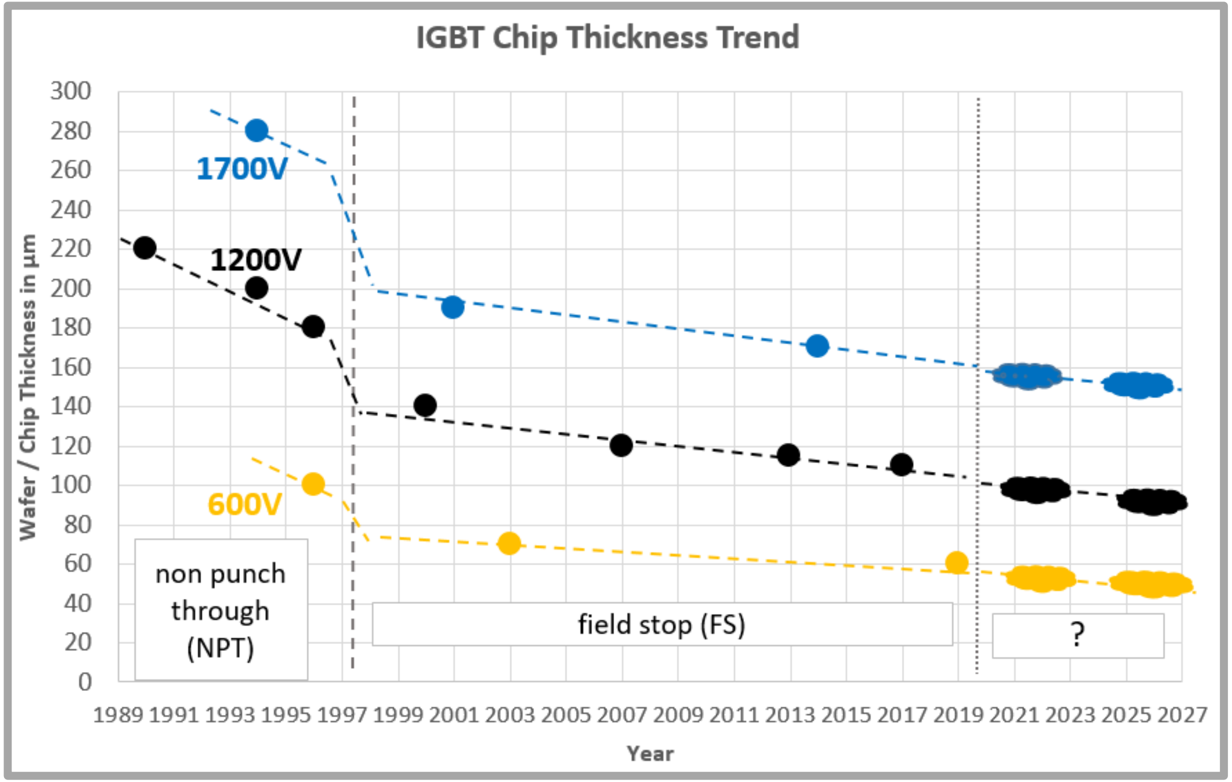


Fig. out of: D. Werber et al., *“A 1000A 6.5kV Module Enabled by Reverse-Conducting Trench-IGBT-Technology,”* in Proc. PCIM, 2015, pp. 351 – 358.

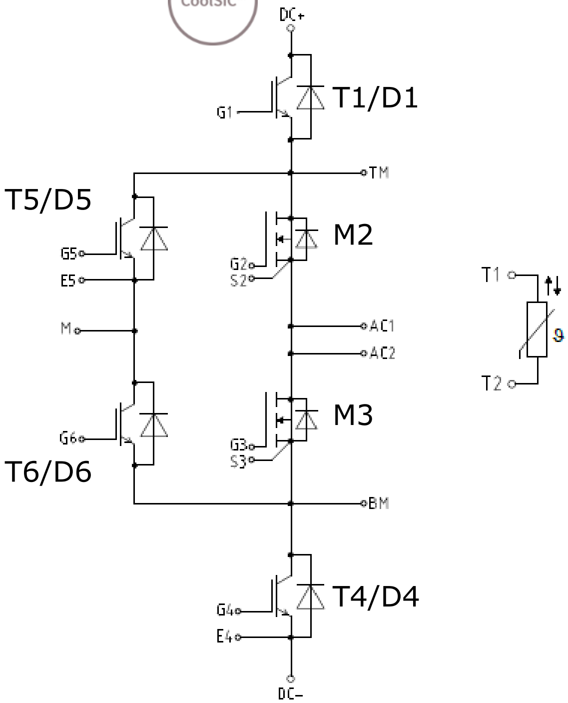
- **Trend to investigate IGBTs with integrated freewheeling diode**
  - Potential “Pro“: Enabling higher power density by using a large chip area for both IGBT and diode function.
  - Potential “Con“: enhanced process complexity and gate-driving complexity

Next IGBT generation vertical structure aspects

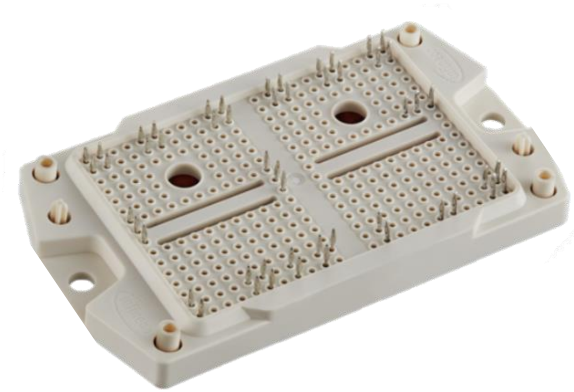


- **It remains attractive to use even thinner chips, as both on-state AND switching losses can thus be reduced.**
  - for a 1200 V IGBT, a chip thickness of about 85µm seems feasible,
  - however, the thinner the IGBT chip, the more critical the ***switching softness***, ***cosmic ray robustness*** and **short-circuit robustness** will become,
  - but countermeasures are available

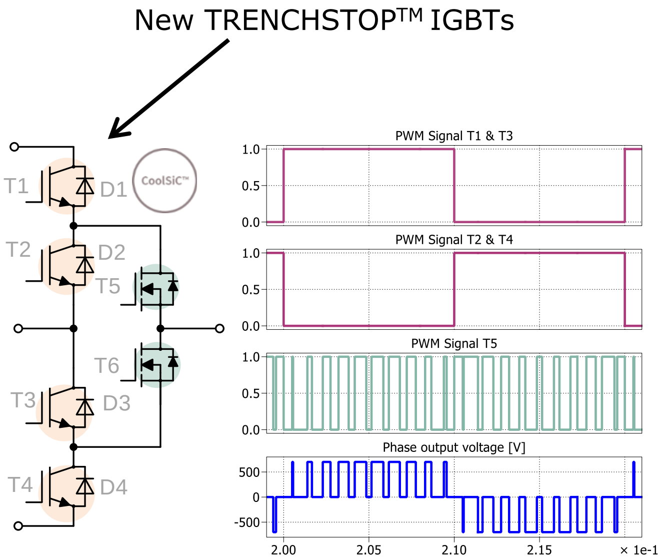
Not necessarily the decision between WBG and silicon is leading to the best solution – a combination might win – example ANPC



Components used	
T1/T4/T5/T6	200A 950V IGBT 7 MPT
D1/D4/D5/D6	200A 950V Diode
M2/M3	1200V SiC MOSFETs: 6mOhm



Merging the strength of silicon and wide band gap delivers cost performance optimized solutions



- ANPC is a topology ideally suited for high voltage, fast switching inverters enabling highest efficiencies
- IGBT/FWD are operated with 50/60Hz → optimized for lowest V_{CEsat}, V_f
- Switching loss only generated in SiC MOSFET
- SiC MOSFET operated in reverse conducting mode → no external SiC FWD needed
- Losses in MOSFET independent of power factor
- Capability of bi-directional power flow – suitable for storage connection as well

Summary

- WBG technologies offer powerful alternatives in selected applications already today
  - Higher cost in several cases compensated by system savings of cost of ownership savings
- Pure focus on WBG might not always give the cost - performance optimized solution
  - Silicon components still with outstanding performance
  - Combination between various technologies might lead to optimum solution