Impact of SiC and RC-IGBT on Electric Railway and EV Drives

Nov. 2nd, 2019

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Fuji Electric Co., Ltd（富士電機）

Outline

□ Introduction

□ RC-IGBT for xEV

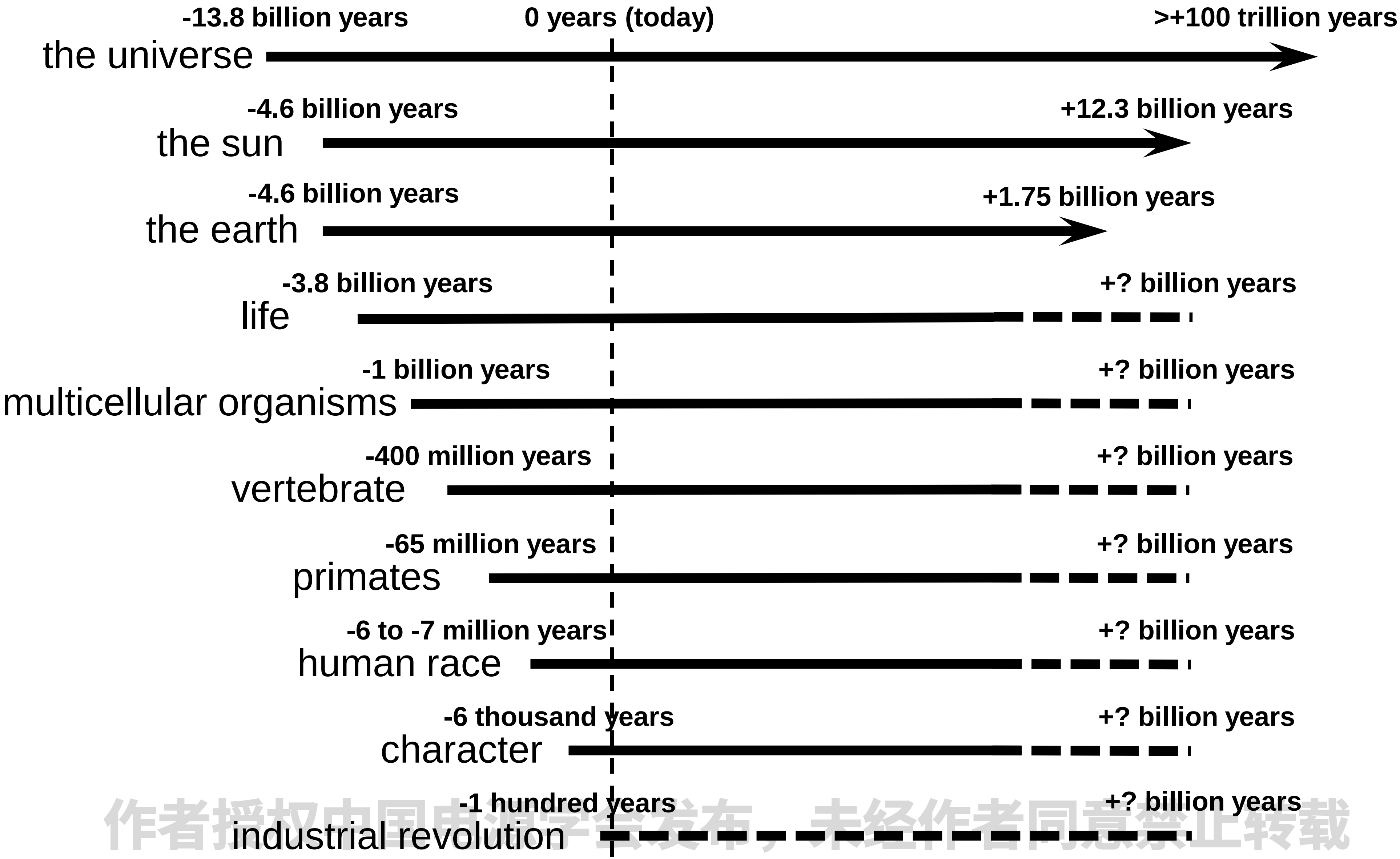
□ SiC-MOSFET

□ Advanced SiC Devices

□ Conclusions

Past, Future, and Today

Fuji Electric
Innovating Energy Technology



-13.8 billion years | 0 years (today) | >+100 trillion years
the universe

-4.6 billion years | +12.3 billion years
the sun

-4.6 billion years | +1.75 billion years
the earth

-3.8 billion years | +? billion years
life

-1 billion years | +? billion years
multicellular organisms

-400 million years | +? billion years
vertebrate

-65 million years | +? billion years
primates

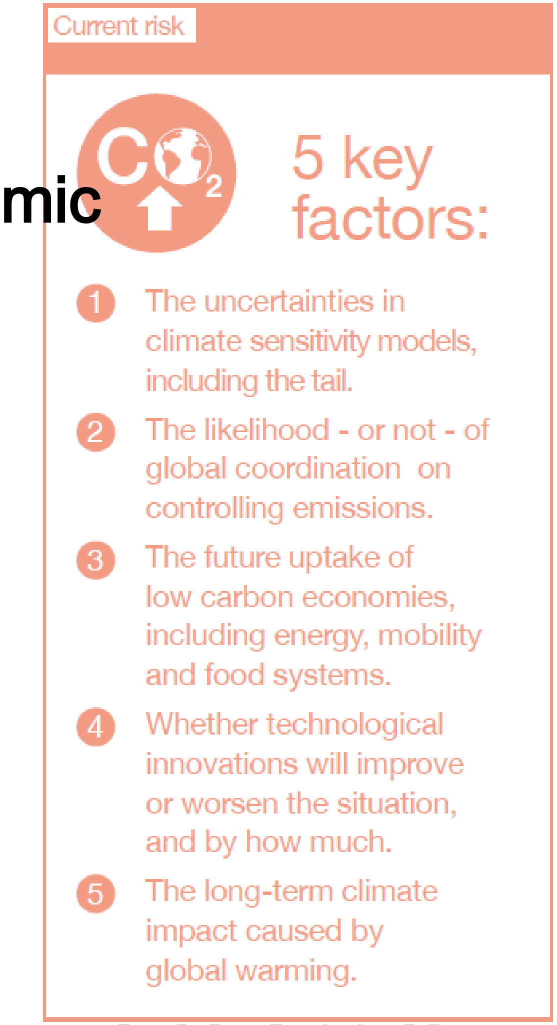
-6 to -7 million years | +? billion years
human race

-6 thousand years | +? billion years
character

-1 hundred years | +? billion years
industrial revolution

12 Risks that Threaten Human Civilization

- ☐ **Extreme Climate Change**
- ☐ **Nuclear War**
- ☐ **Global Pandemic**
- ☐ **…**


Current risk

5 key factors:

1. The uncertainties in climate sensitivity models, including the tail.
2. The likelihood - or not - of global coordination on controlling emissions.
3. The future uptake of low carbon economies, including energy, mobility and food systems.
4. Whether technological innovations will improve or worsen the situation, and by how much.
5. The long-term climate impact caused by global warming.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Executive Project Manager Global Risks
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or

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James Martin Research Fellow
Future of Humanity Institute
Oxford Martin School
University of Oxford

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Source: 12 Risks that threaten human civilization
Global Challenges Foundation, Feb. 2015

Resolution of UNs 70th General Assembly

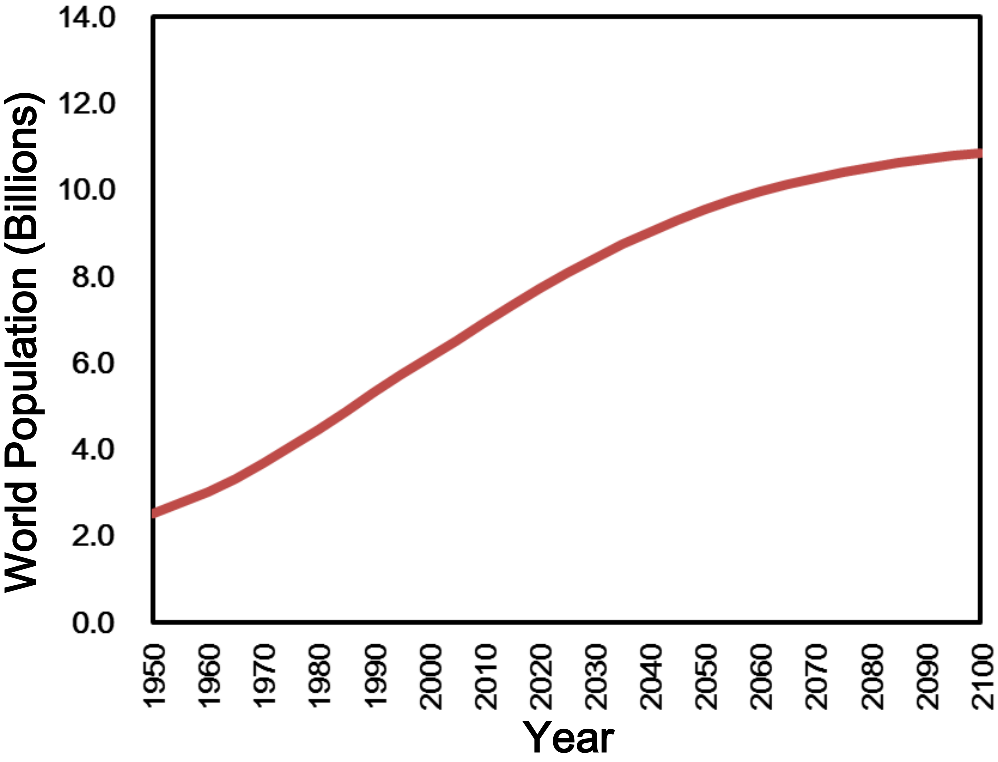
Resolution adopted by the General Assembly on 25 September 2015

[*without reference to a Main Committee (A/70/L.1)*]

70/1. Transforming our world: the 2030 Agenda for Sustainable Development

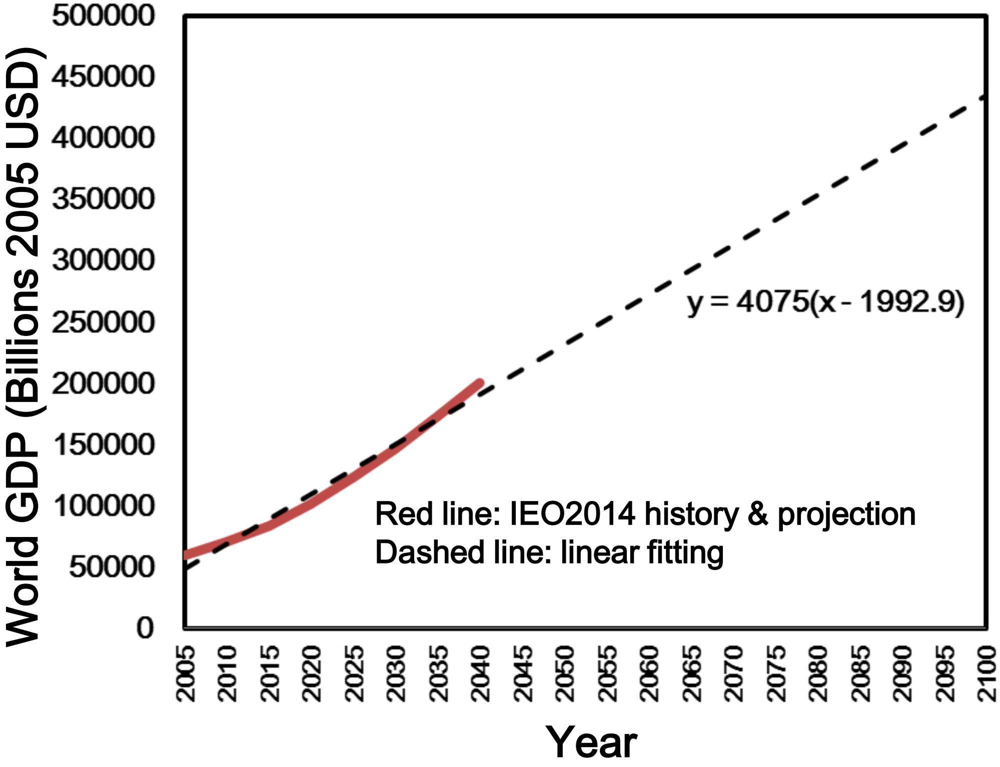
What will come in this century?

□ Population grows 1.5 times



Source: World Population Prospects: The 2012 Revision
Population Division of the Department of Economic
and Social Affairs of the United Nations Secretariat

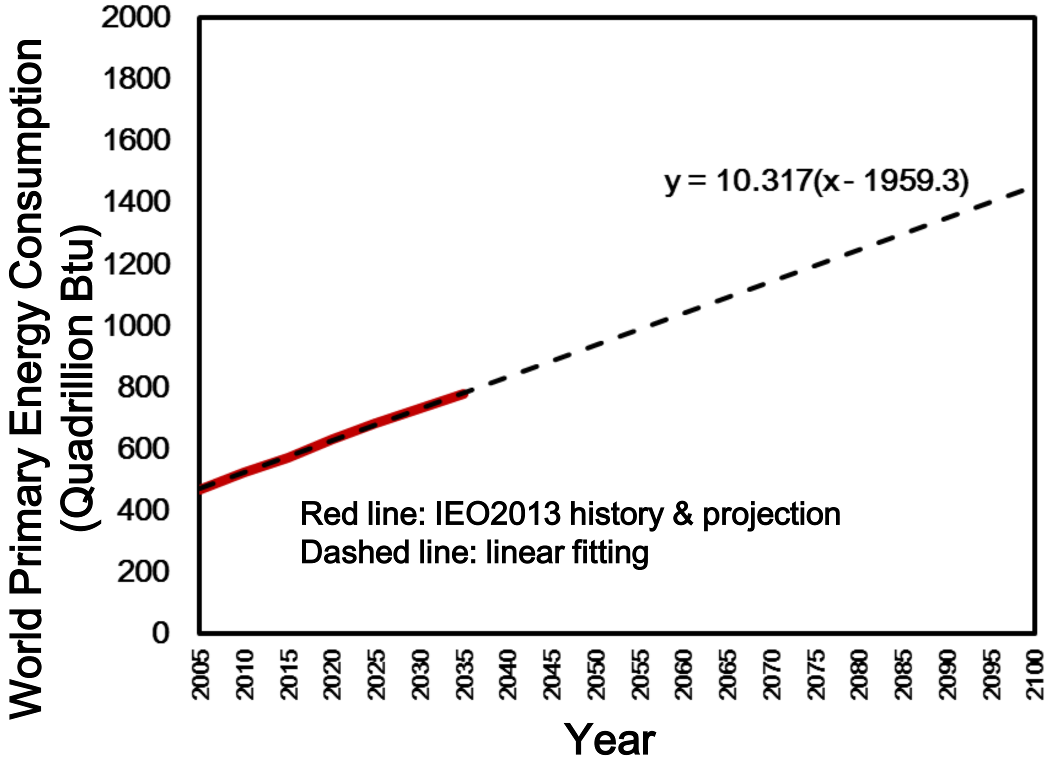
□ GDP more than 4.5 times



Source: International Energy Outlook 2014, Reference case,
U.S. Energy Information Administration

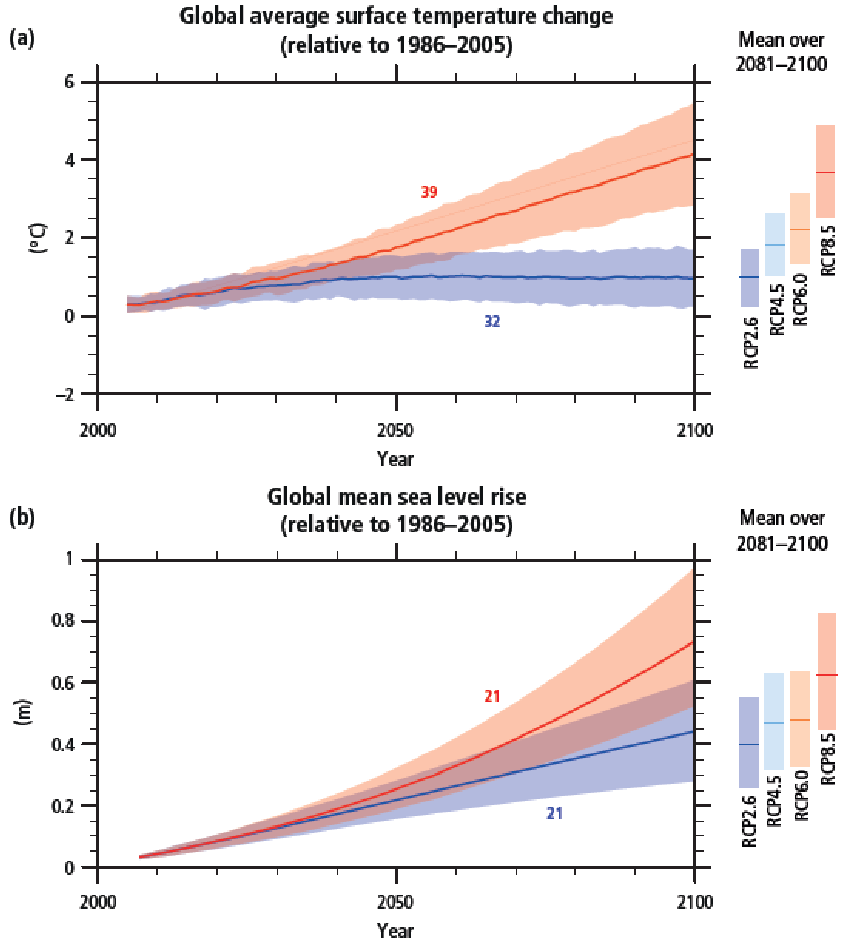
Energy, CO_2 Emission, Climate Change

- Energy consumption 2.5 times



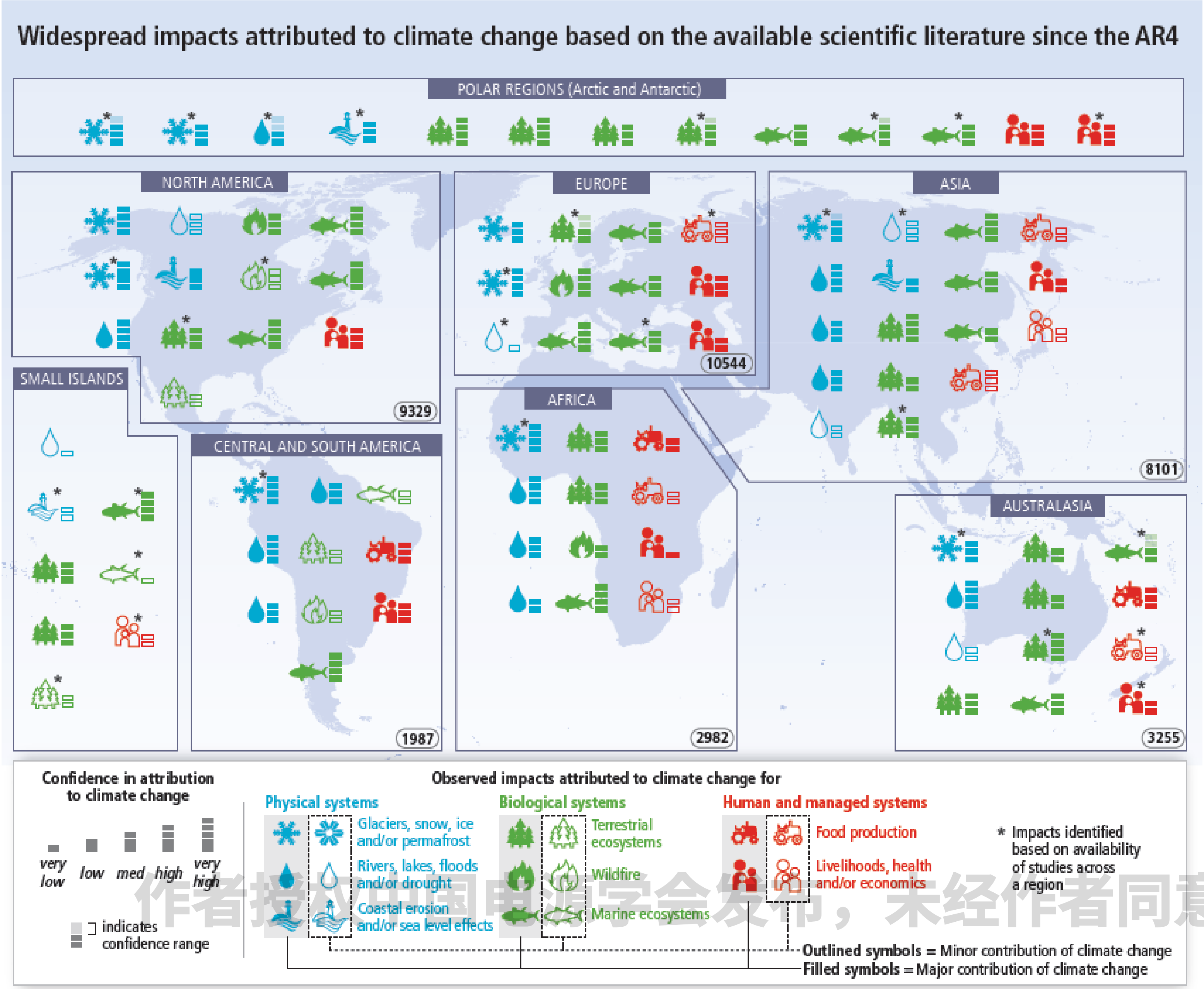
Source: International Energy Outlook 2013, Reference case,
U.S. Energy Information Administration

- Temperature rise 1-4 degree
- Sea level rise 0.4-0.8 meter



Source: IPCC 5th Assessment Report
Climate Change 2014 Synthesis Report, 2015
Figure SPM.6.

Widespread Impacts of Climate Change



Widespread impacts attributed to climate change based on the available scientific literature since the AR4

Source:
IPCC 5th Assessment Report
Climate Change 2014 Synthesis Report, 2015.
Figure SPM.4.

COP21 and Paris Agreement

United Nations

FCCC/CP/2015/10/Add.1

Framework Convention on
Climate Change

Distr.: General
29 January 2016

Original: English

Conference of the Parties

Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015

Addendum

Part two: Action taken by the Conference of the Parties at its twenty-first session

Contents

Decisions adopted by the Conference of the Parties

Emphasizing with serious concern the urgent need to address the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels,

What we should do

as power electronic R&D or industries are

- switch from fossil to renewable energies
- shift from car, jet, and combustion engines to xEV and electric transportations
- increase efficiency of power generation, transmission, and conversion
- reduce consumption, increase reuse and recycle of limited natural resources including Cu and Iron in power electronic systems

to establish a sustainable society

“The eyes of all future generations are upon you.

"And if you choose to fail us, I say: We will never forgive you. We will not let you get away with this. Right here, right now is where we draw the line. The world is waking up. And change is coming, whether you like it or not." Greta Thunberg told world leaders Sep. 23rd, 2019, speaking at the U.N. Climate Action Summit in New York City.

Photo by Johannes Eisele from Agence France-Presse via Getty Images

☐ RC-IGBT for xEV

Fuji Electric Contributions to xEV

Fuji Electric
Innovating Energy Technology

2 in 1 IPM

Production

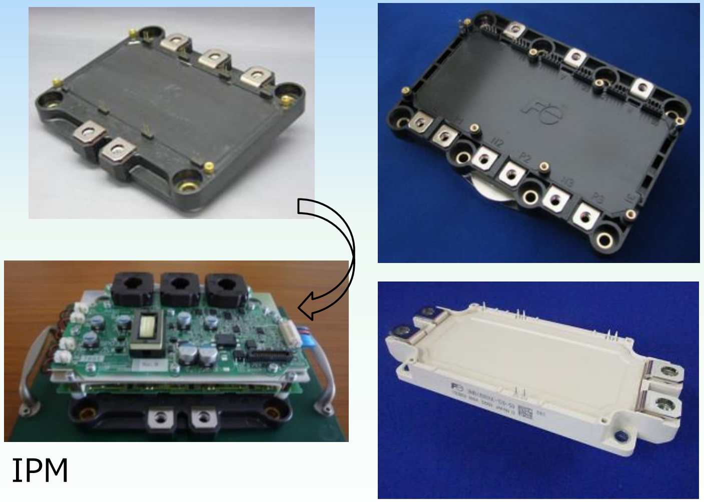
Buck boost converter

Company T : HEV

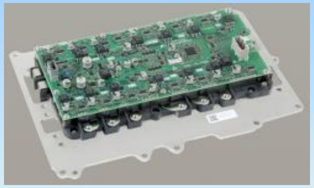
Module

Production

Inverter



14 in 1 IPM



Production

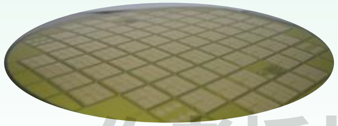
2 Inverters with buck boost converter

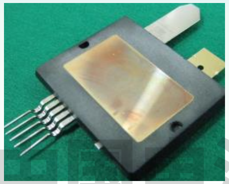
Company H : HEV/PHEV

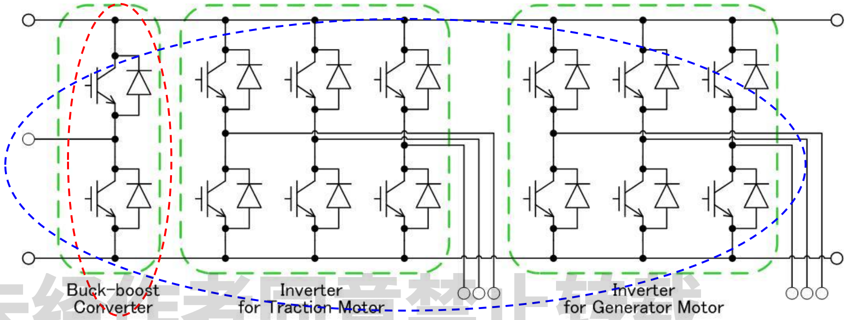
Power chip for double side cooling system

Production
Power chip by Fuji

Company D : HEV

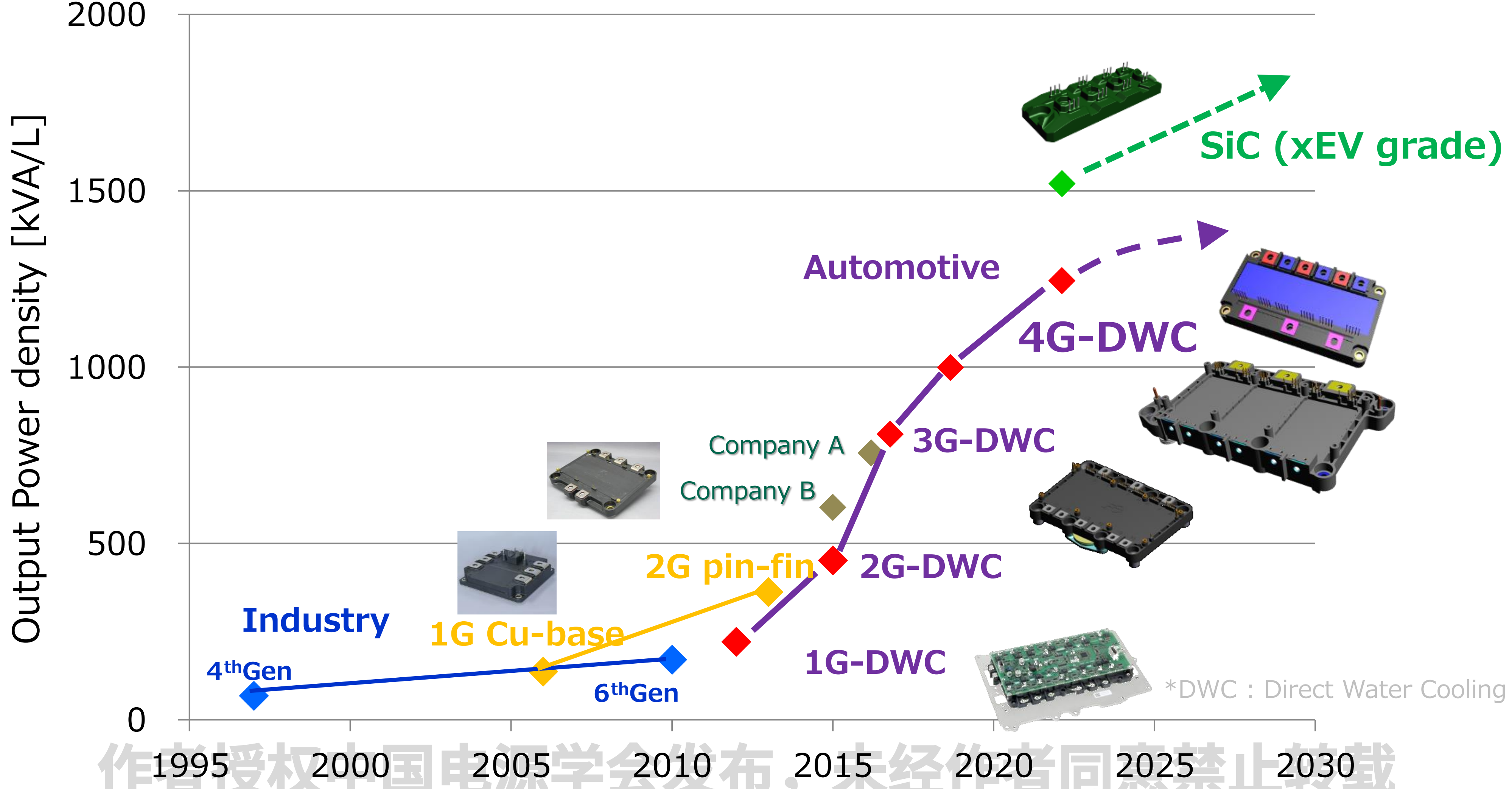






IGBT Module Power Density Trend

Higher power density challenge with the best integration in chip-package-thermal management engineering.



＊Output Power density [kVA/L] = Max output power [kVA] / Module volume [L] in continuous

Important Tech. for Auto. IGBT Modules

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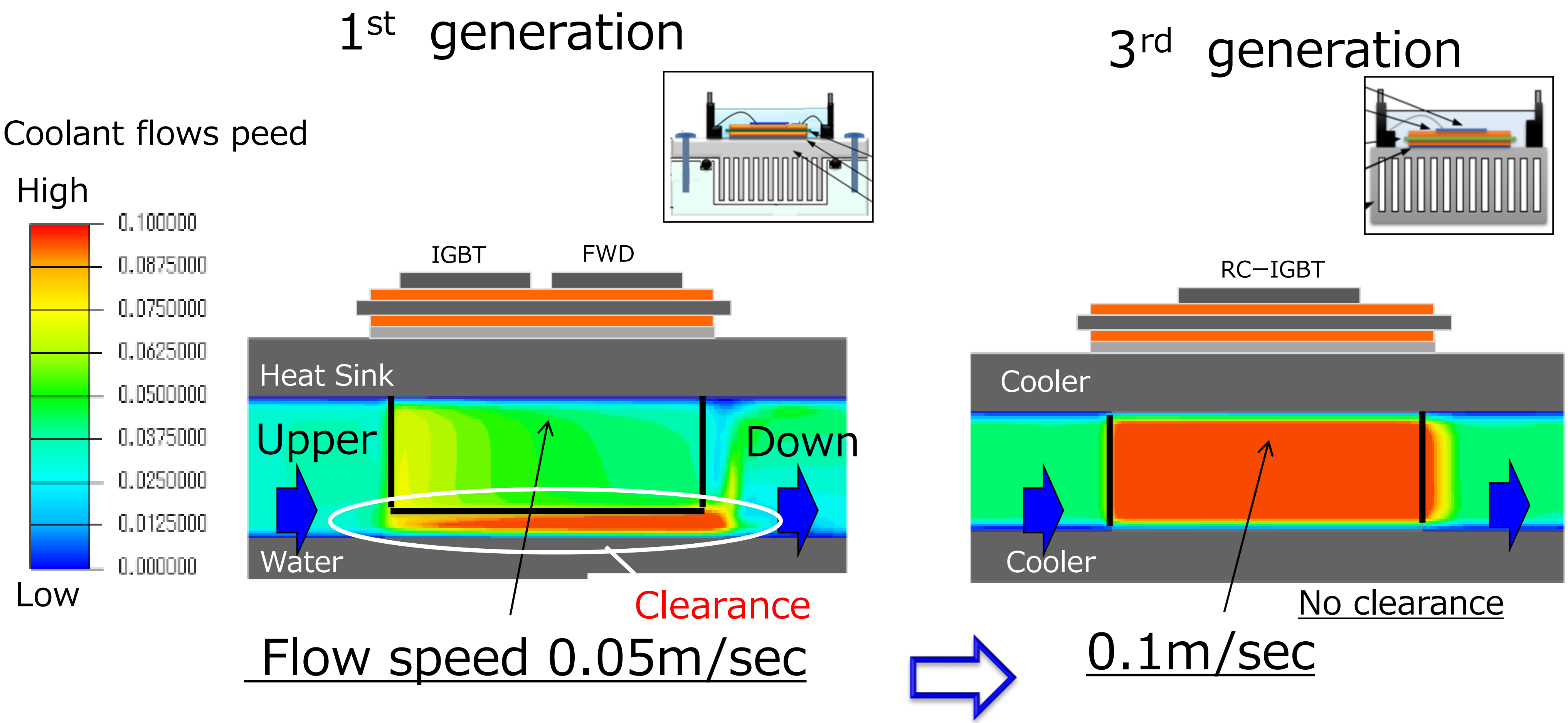
- ☐ Direct water cooling (DWC) aluminum fin
  to reduce Rth, pressure loss, weight, and thickness

- ☐ RC-IGBT from 3G DWC
  to reduce die, DCB, module area and Rth

- ☐ Lead-Frame wiring from 4G DWC
  to reduce size, Ls, Rth, Tjpeak, and to increase I^2t

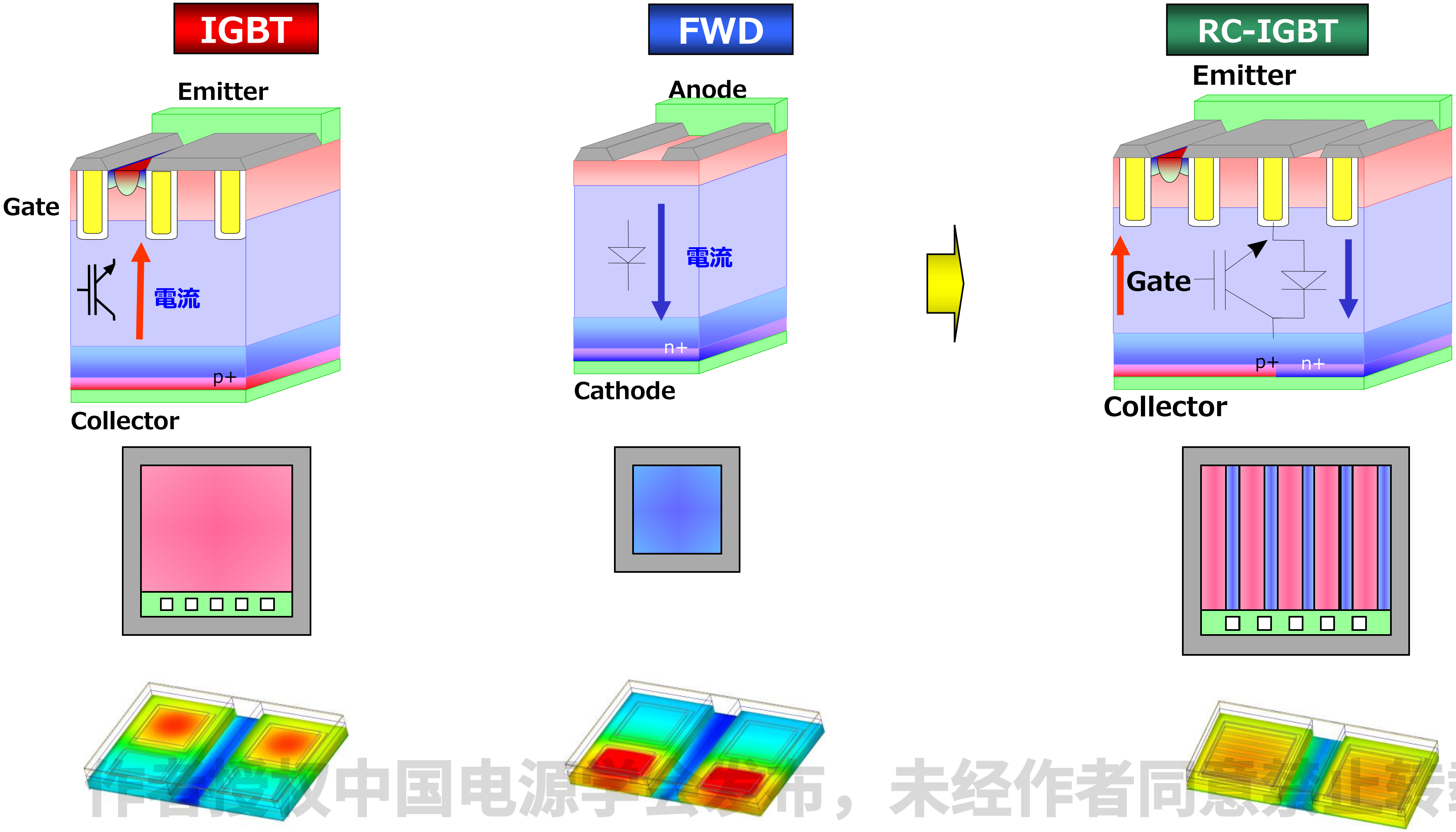
3G DWC: Cooling Performance Improved



- Coolant flow speed was optimized to flow it near chip area, resulting in **Rth reduction by 30%.**

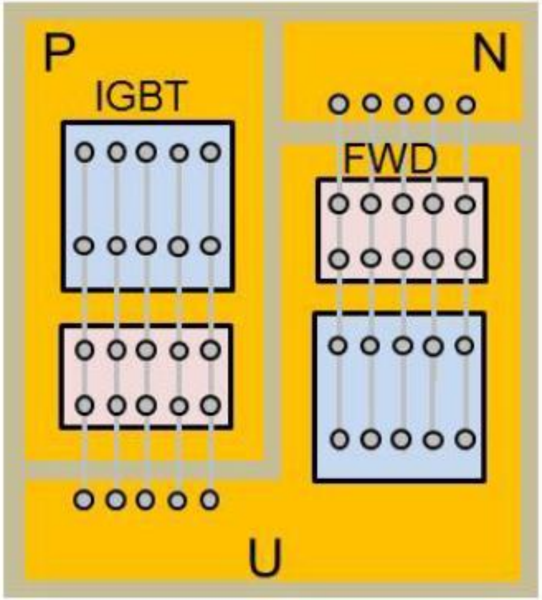
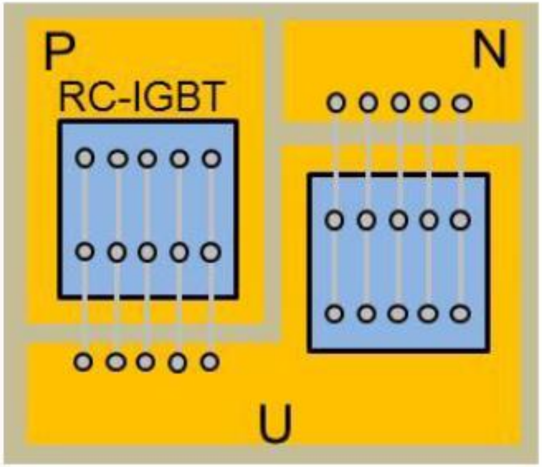
RC-IGBT from 3G DWC

Monolithic integration of IGBT/FWD,
Additional die shrink available; $Rth_{j\text{-}c}$↓↓, compact, reduce $$$



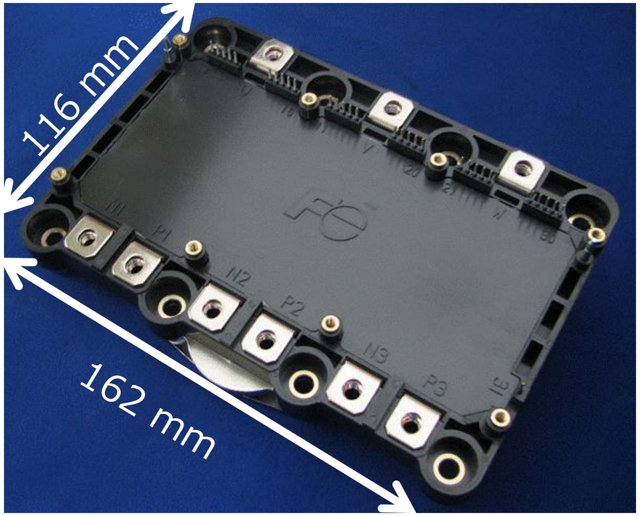
RC-IGBT from 3G DWC

Reduction of DCB area by 25%
Reduction of parasitic inductance of emitter-to-DCB wiring by 22%

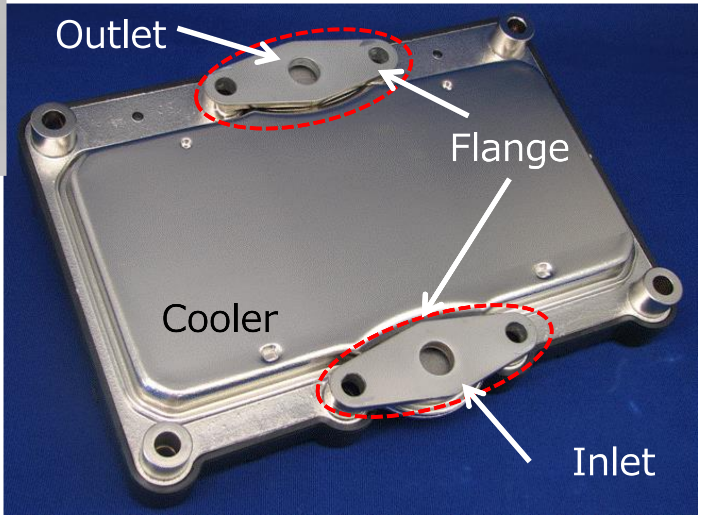
	Conventional IGBT and FWD	Newly developed RC-IGBT
A general Substrate layout of half-bridge circuit		
Ratio of substrate size	1	0.75
Ratio of length between P and N terminal	1	0.78

A general substrate layout of half-bridge circuit.

3G DWC 6in1 RC-IGBT under MP from 2017



Thinner than one RMB coin diameter !!



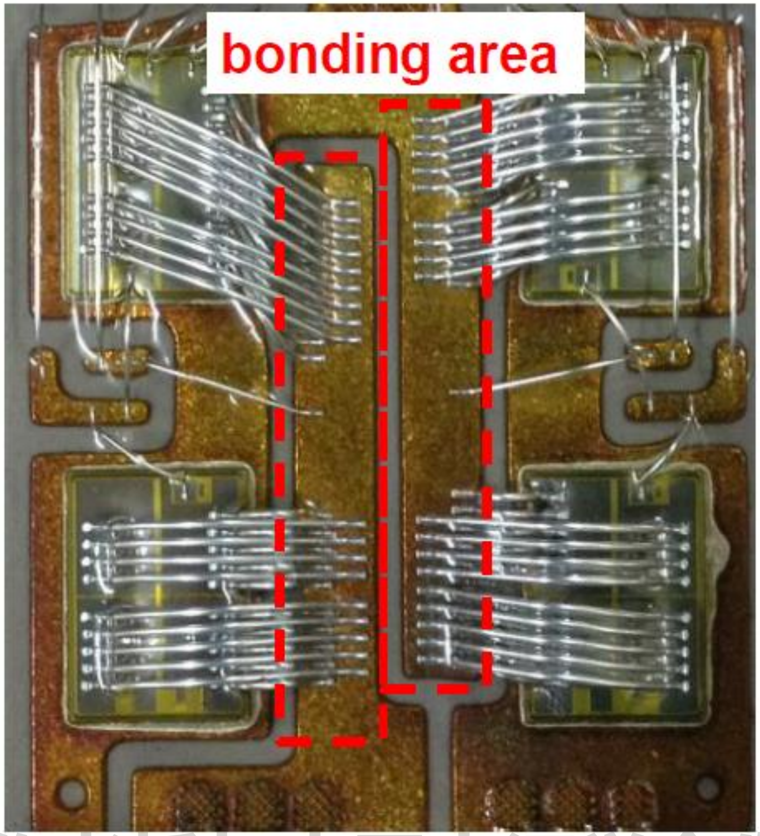
Item	Value
Collector-Emitter voltage	750 V
Implemented Collector current	800 A
Saturation voltage at 175°C	1.65 V
Thermal resistance at 10L/min	0.141 °C/W
Continuous operating junction temperature	175 °C
Size	162×117×24 mm
Weight	570 g
Target to motor output power to be applied	100-150 kW

- M653 is high power, light-weight, small size and ultra-thin.

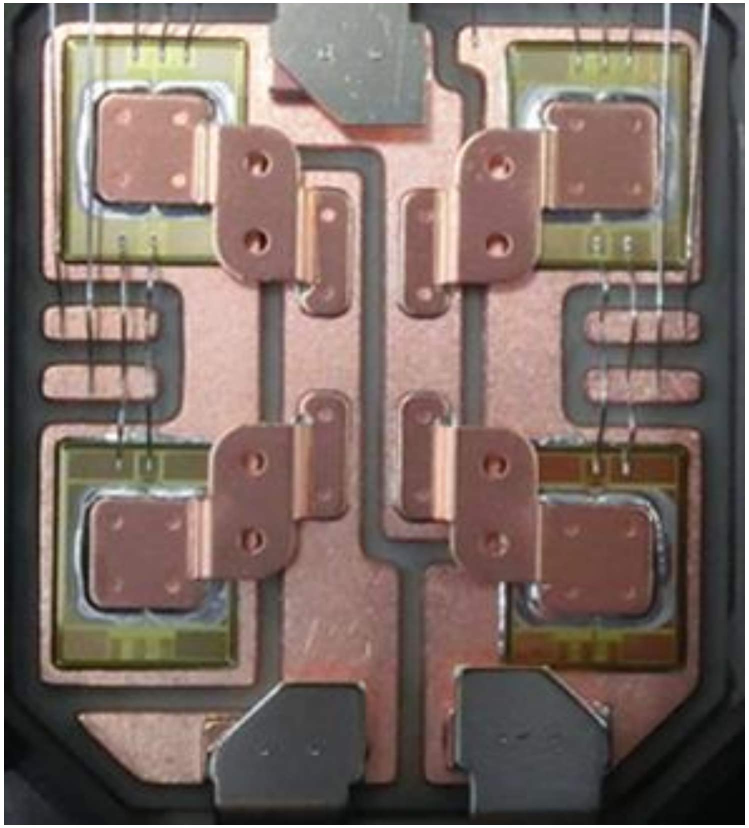
Lead-Frame Wiring from 4G DWC

Support for large current

Reduction of parasitic inductance of emitter-to-DCB



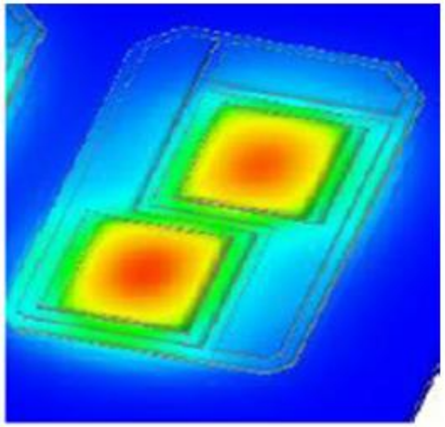
Aluminum-wire-bond wiring



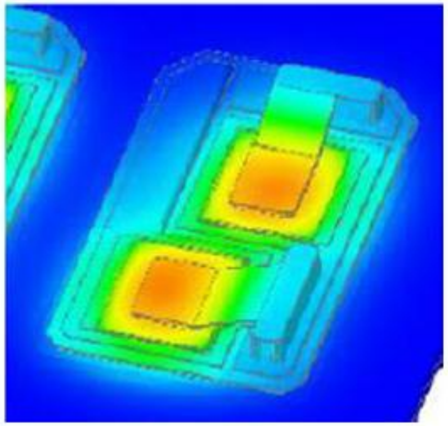
Lead-frame wiring

Lead-Frame Wiring from 4G DWC

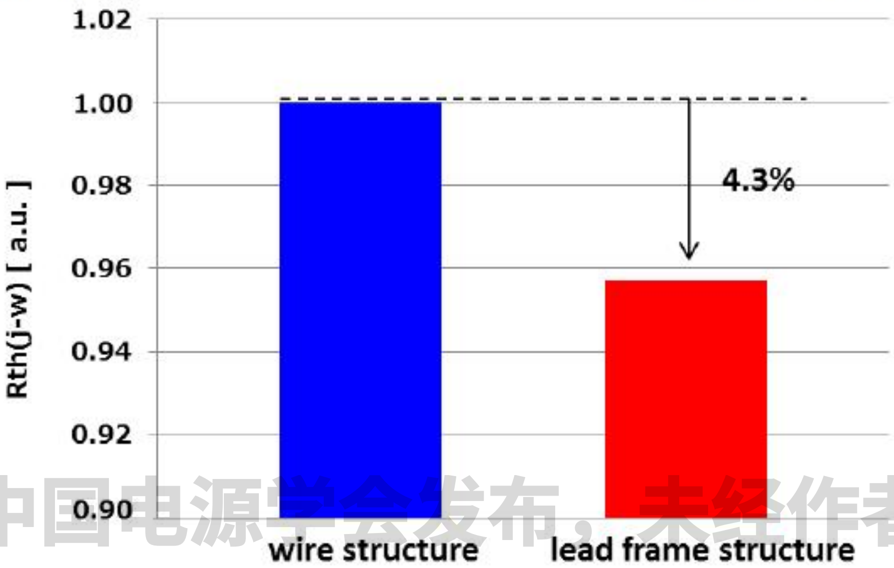
Reduction of Rth by 4.3%
Reduction of peak chip-surface temperature



wire structure



lead frame structure



□ SiC-MOSFET

Application Examples of SiC Devices

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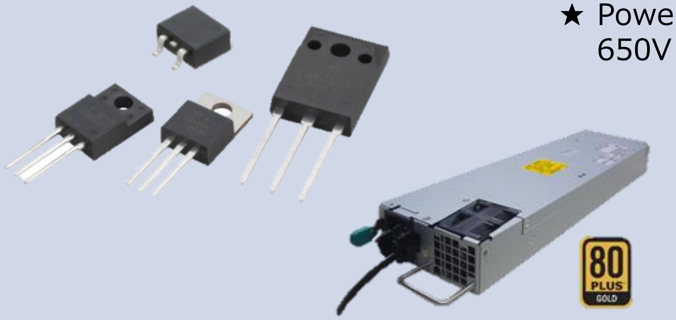
- ☐ **Application of SiC is gradually widening, examples at Fuji Electric.**

CY2012 2013 2014 2015 2016 2017 2018 2019

Discrete SiC-SBD



★ Power Supply
650V SiC-SBD

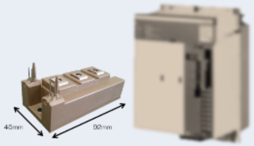
★ EV charger
1200V SiC-SBD

SiC-SBD Hybrid Module

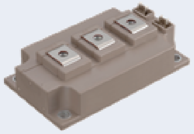
★ General purpose INV
600V,1200V SiC
Hybrid Module

★ Traction propulsion
3300V SiC
Hybrid Module

★ Servo, Robot
1200V SiC
Hybrid Module



★ UPS
1200V SiC
Hybrid Module

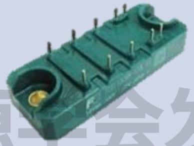


★ HEV Racing Car
1200V SiC
Hybrid Module

All-SiC Module

★ PCS
1200V
All-SiC Module

★ Mega solar PCS
1200V
All-SiC Module



★ IP6x INV
1200V Trench
All-SiC Module

☆ Premium INV
☆ APS and Inverter
for traction
1200V Trench
All-SiC Module

Environment-Resistant Inv. Use All-SiC Module

- **Loss reduction removed cooling fans, and thus realized environment-resistant, maintenance-free inverters.**

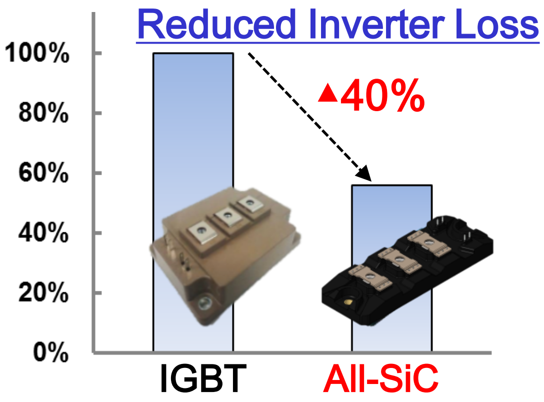
Features

◆Best use of low loss and high temperature operation in SiC devices

- All closed self-cooling structure, as well as downsizing
- Outdoor installation, application for environment with corrosive gases

400V/37kW

Performance Comparison



Application

- Factory production for outdoor harsh environment

Power Supply / Capacity

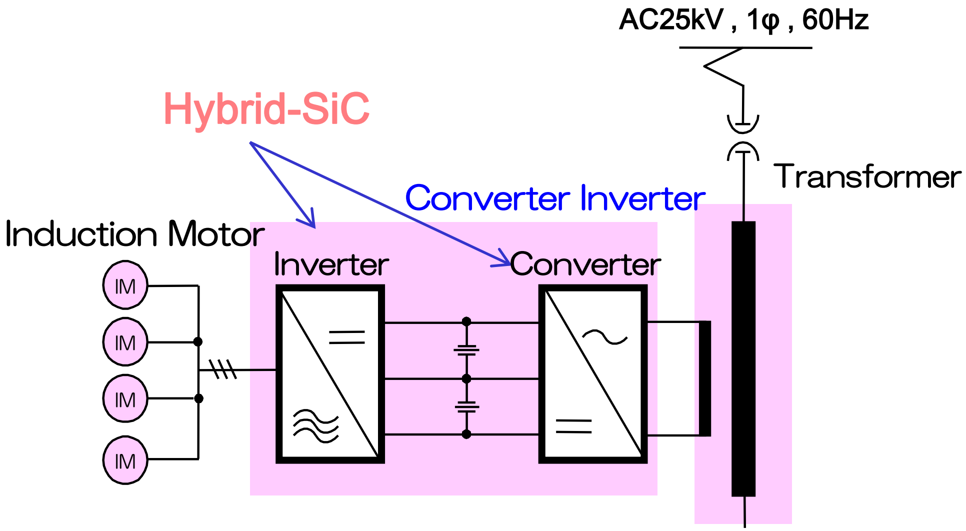
3 phase, 400V/3.7 ~ 37kW (Sales started)

Next Gen. Shinkansen Use Hy-SiC Module

□ **Rectifiers and inverters in N700S propulsion systems utilize Hybrid-SiC modules.**
□ **Trial operation started in April, 2018.**


Photograph by Central Japan Railway Company

N700S Test Train



Driving System for Trains

3.3kV-1.8kA Rated

190×140mm
SiC-Hybrid Module

Converter Inverter

Comparison with conventional N700A

Volume : ▲10%

Weight : ▲13%

New VVVF Inv. Use Hy-SiC Module

☐ **Reduction of volume is -64%, reduction of weight is -45%.**
☐ **Commercial operation started in Oct., 2018.**

New Technology

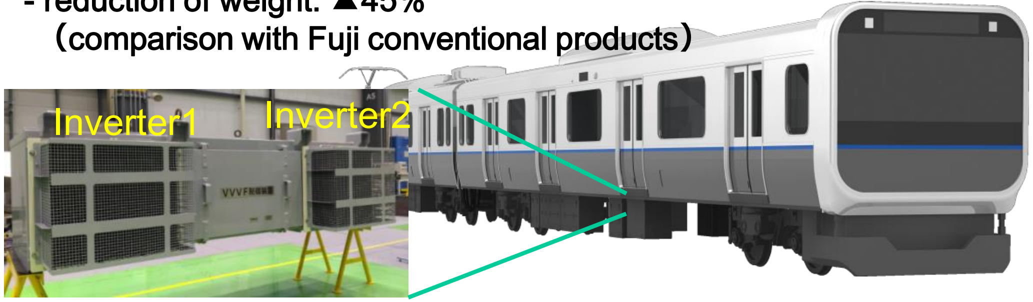
Use of SiC Devices

Inverter Loss:
▲20% Reduction

■Ratings：3.3kV／1.2kA
■Structure：
SiC Hybrid Module
IGBT(7G)＋SiC-SBD

◆720kW Rated Inverter
（2-inverter unit, 4-motor drive）

- Downsize:▲64%,
- reduction of weight: ▲45%
（comparison with Fuji conventional products）



VVVF Inverter

New Technology

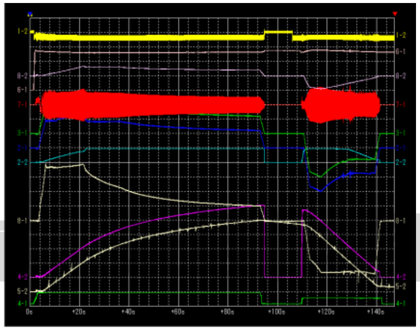
Running Wind Cooling

No need for heat pipe in cooling body, simple brazing type, unit with small size and light weight

■Design based on wind-tunnel tests using fluid analysis and miniature model for train
■Confirmation of targeted performance by stationary evaluation

New Technology

Speed Sensorless Control



Speed Sensor is not necessary. Simplified interconnects, high reliability

■Torque error: ±５%
Ride quality improved

Hy-SiC Module Used in Conventional Lines

□ **Sanyo Electric Railway Co., Ltd. uses Hybrid-SiC Modules for its VVVF inverters.**

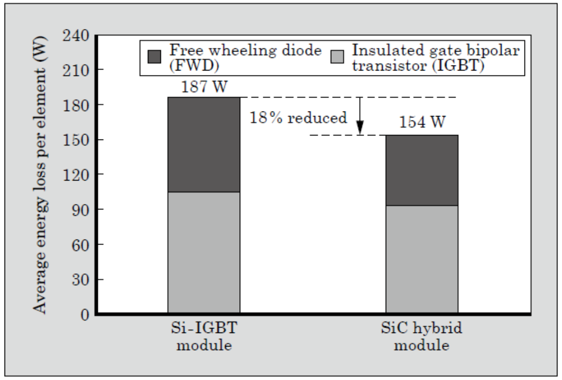
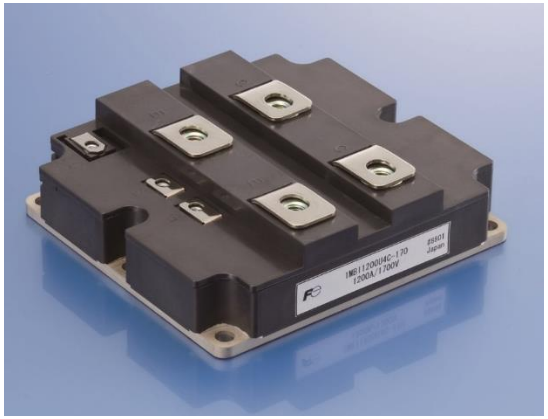


Fig.5 Energy loss comparison

1in1 1200A SiC-Hybrid Module



VVVF Inverter

https://www.fujielectric.co.jp/about/company/gihou_new_2019/pdf/FEJ-2019-S01.pdf

All-SiC Module Used in Conventional Lines

☐ **All-SiC modules are started to be used for VVVF in Odakyu and Marunouchi lines.**

Mitsubishi module for

Odakyu line (2015/1)

https://www.zaikei.co.jp/article/20140501/191409.html

Toshiba module for

Marunouchi line (2019/2)

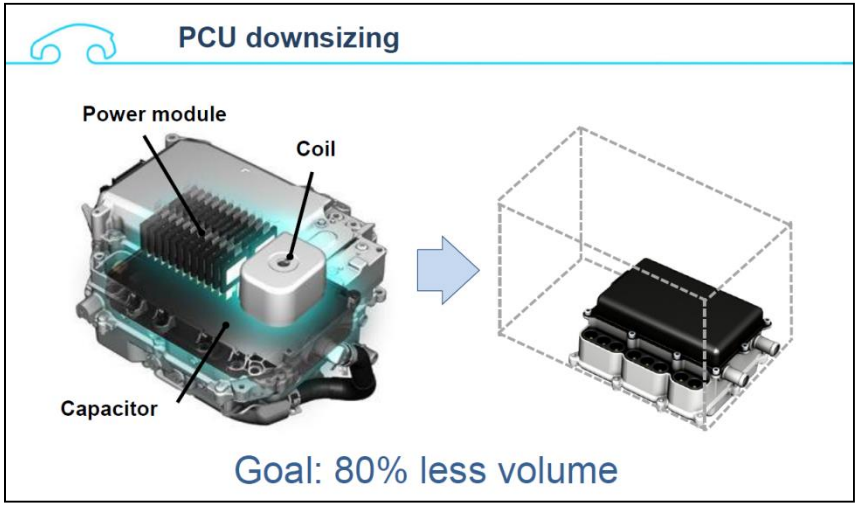
https://project.nikkeibp.co.jp/ESG/atcl/case/010900013/

Toyota Carried out Public-Road Operation

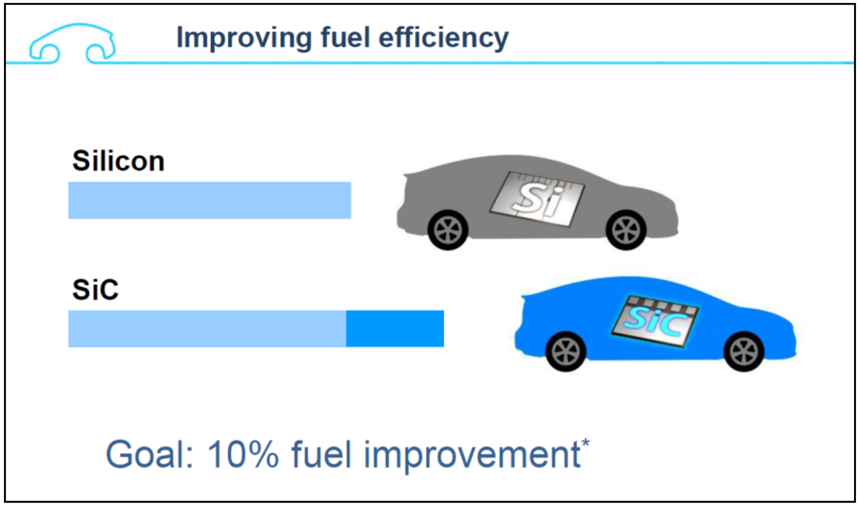
January, 2015 - Camry hybrid prototype with All-SiC PCU and fuel cell bus with SiC-SBD

豊田

- In the Camry hybrid prototype, Toyota is installing SiC power semiconductors (transistors and diodes) in the PCU's internal voltage step-up converter and the inverter that controls the motor.
- The bus features SiC diodes in the fuel cell voltage step-up converter, which is used to control the voltage of electricity from the fuel cell stack.


PCU downsizing

Goal: 80% less volume


Improving fuel efficiency

Goal: 10% fuel improvement*

http://newsroom.toyota.co.jp/en/detail/5692153
http://newsroom.toyota.co.jp/en/detail/2656842

Honda Started Small Number Production

March, 2016 – Clarity FC with All-SiC FC VCU released

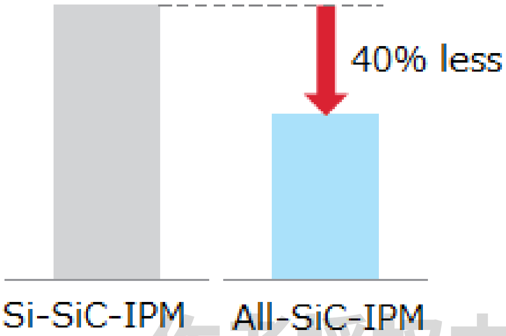
Sold 220 units by June, 2018

本田

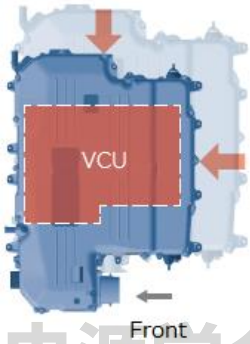
FCVCU

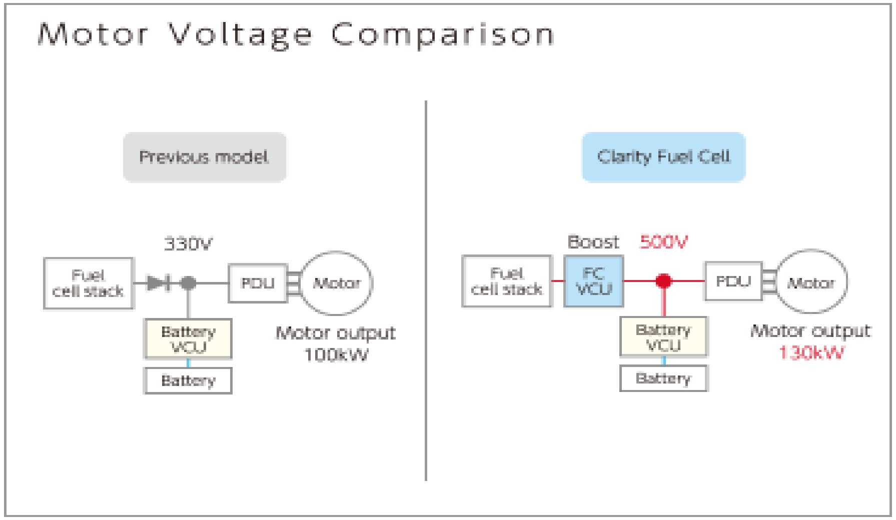
All-SiC power modules installed
- ✓ 30kHz
- ✓ 40% less volume

- ➢ Sold more than 200 units by March 2018.
- ➢ Cruising range (for reference) is approximately 750 km.



Downsizing image





http://world.honda.com/CLARITY/

http://world.honda.com/automobile-technology/engineer-talk/CLARITY/

http://www.honda.co.jp/factbook/auto/CLARITY_FUEL_CELL/201603/P14.pdf

Toyota Sells FC Bus using SiC-SBD

February, 2017 - Toyota started to sell fuel-cell bus using SiC-SBD for boost converter

March, 2017 - Tokyo Metropolitan Bus started commercial operation of SiC FC bus and announced the plan to increase the number of SiC FC bus up to more than 100 by 2020

豊田

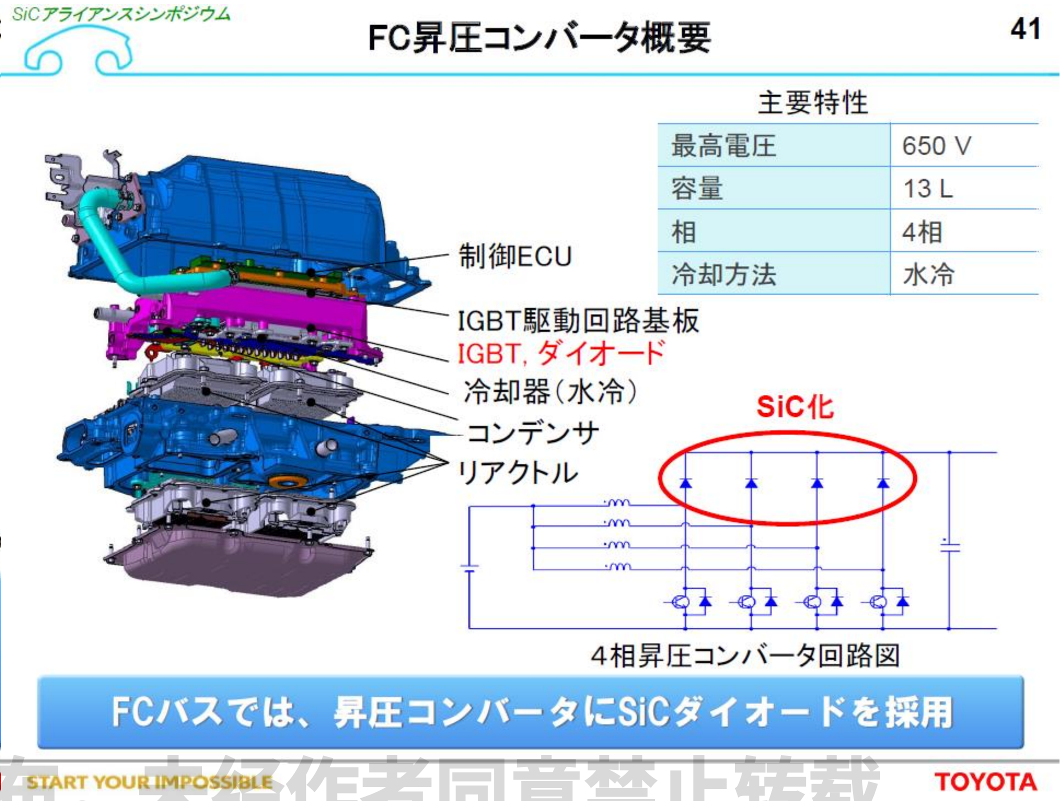
SiCアライアンスシンポジウム

燃料電池バス：SiCダイオード使用

出典:トヨタ自動車　ニュースリリース資料(2017 年2 月24

- 2017年2月より、FCバスの販売を開始
- 東京都へ2台納車、2017年3月より都営バスとして営業運行中
- 東京オリンピック・パラリンピックに向けて100台以上の導入予定

START YOUR IMPOSSIBLE　TOYOT



SiCアライアンスシンポジウム

FC昇圧コンバータ概要

41

主要特性

最高電圧	650 V
容量	13 L
相	4相
冷却方法	水冷

4相昇圧コンバータ回路図

FCバスでは、昇圧コンバータにSiCダイオードを採用

START YOUR IMPOSSIBLE　TOYOTA

Source: K. Hamada from Toyota, SiC alliance presentation, March 2018.

Keikyu Started FC Bus using SiC-SBD

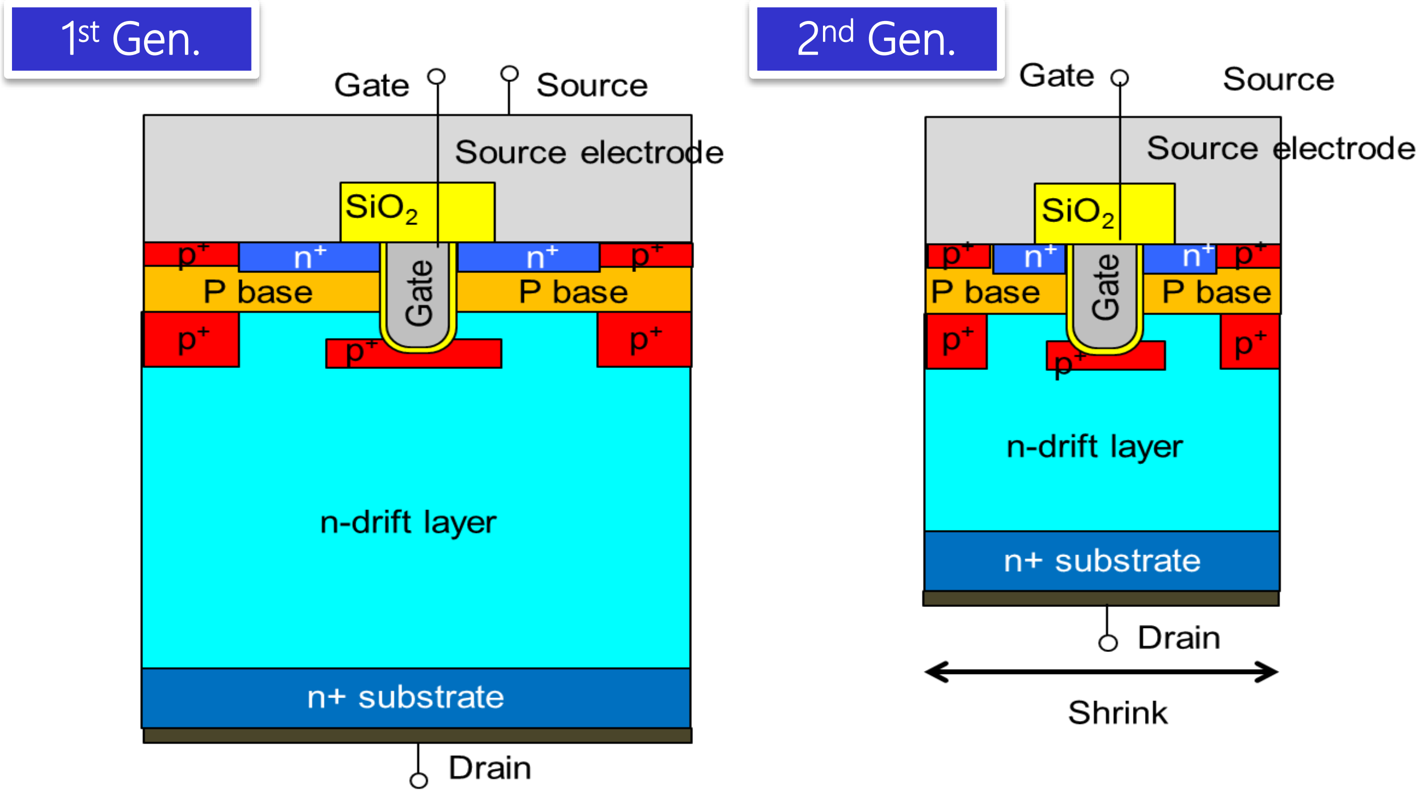
Fuji Electric
Innovating Energy Technology

February, 2019 – Keikyu Bus started operation of FC bus “SORA” using SiC-SBD in Odaiba area.

https://response.jp/article/2019/02/25/319479.html

2nd generation trench gate SiC MOSFETs

Cross-Section Structure of SiC MOSFETs



comparison of characteristics (1200V)

	1st Gen. trench gate SiC MOSFETs	2nd Gen. trench gate SiC MOSFETs
Normalized RonA	1.00	0.77
$V_{GS(th)}$	5.1V	5.0V
Recommended Gate Voltage	+20/-3V	+15/-3V

Electrical performance of All-SiC Module

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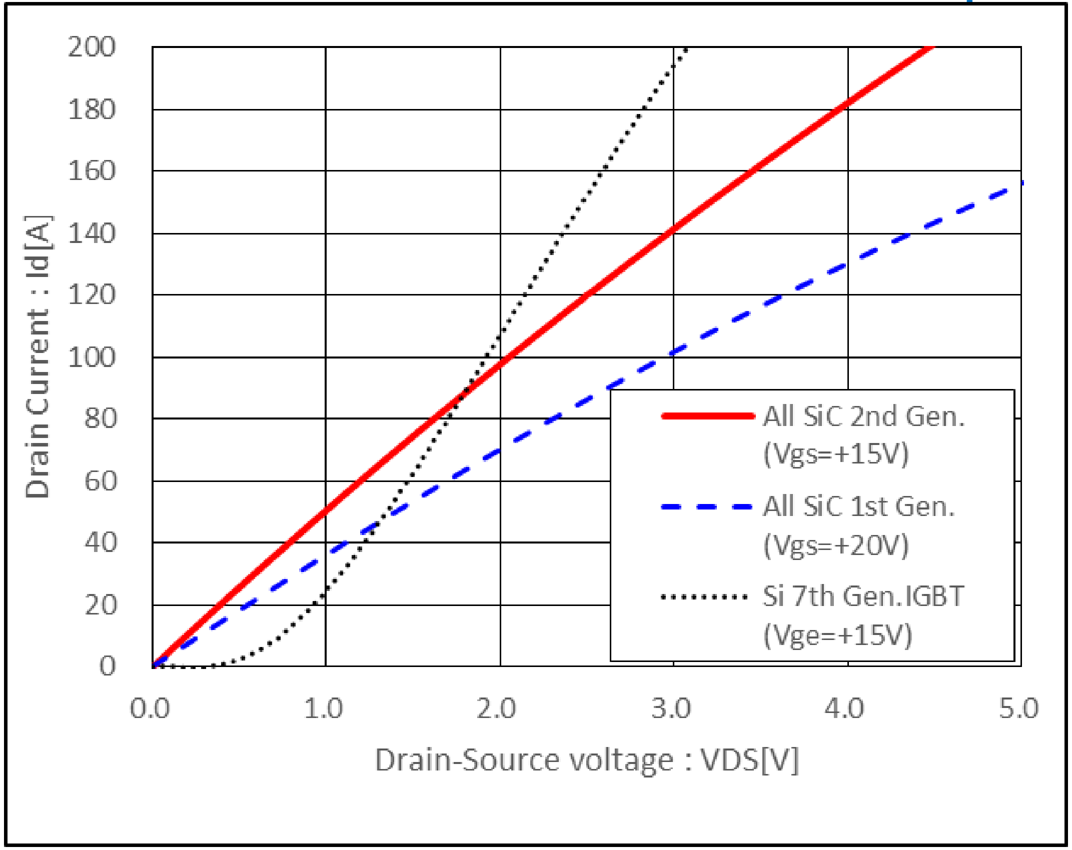
Si 7th Gen./All-SiC1st Gen./All-SiC2nd Gen. output characteristic

1200V/100A

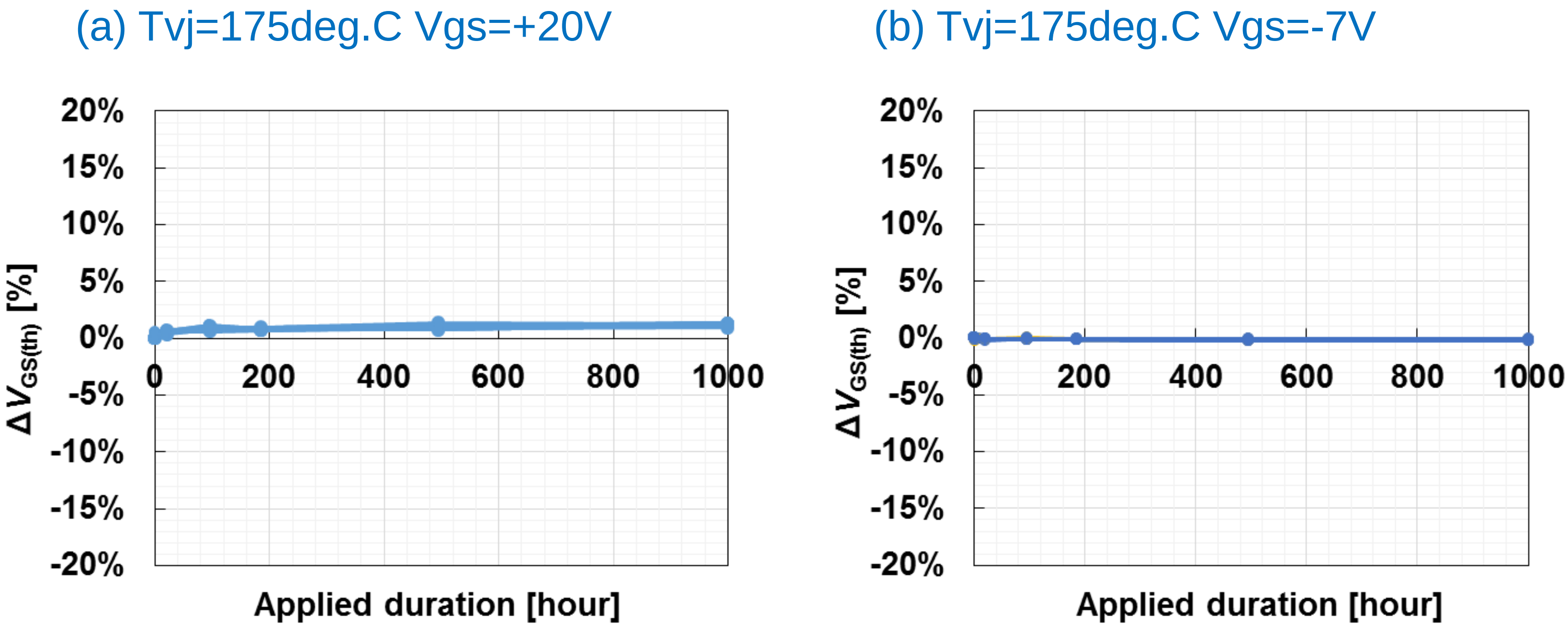


All-SiC output characteristic was improved!

→The on-state voltage of all-SiC module was reduced under 85A.

Electrical performance of All-SiC Module

Reliability test results under DC biased condition to All-SiC 2nd Gen.



Gate characteristics of 2nd generation trench gate SiC MOSFETs is stable.
→Realize high reliability for All-SiC modules.

Lineup plan for All-SiC Module

All-SiC lineup plan

		Package Type	Small 1B	Small 2B	62mm STD	HPnC
		Size (WxDxH)	62.8x33.8x12 mm	56.7x62.8x12 mm	62x108x30.5 mm	100x140x38 mm
Rated voltage	MOSFET generation	Equivarent Circuit				
1200V	2nd generation Trench gate	2in1	~100A	~200A	~600A	N/A
		6in1	~50A	~100A	N/A	N/A
1700V	2nd generation Trench gate	2in1	N/A	N/A	~400A	TBD
3300V	1st generation Trench gate	2in1	N/A	N/A	N/A	~750A

The product lineup will realize coverage of the wide range inverter capacity.

□ Advanced SiC Devices

6.5kV SiC Superjunction MOSFET

☐ 7.8kV 17.8mΩcm² SiC Superjunction MOSFET breaking the 4H-SiC unipolar limit.

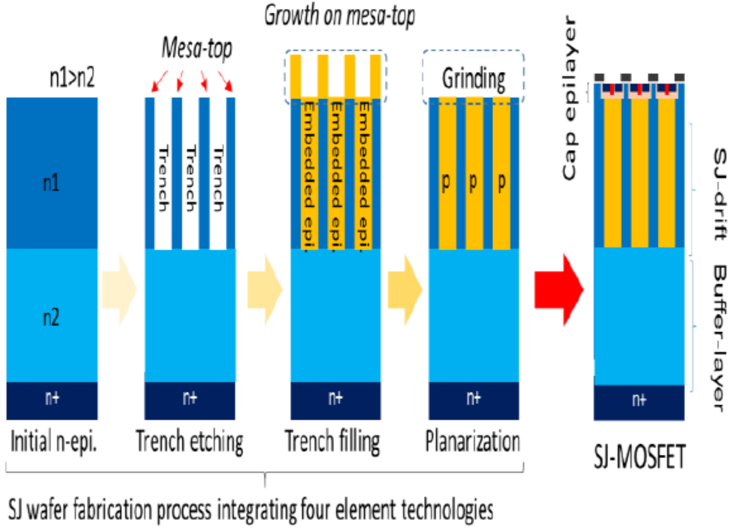


Figure 1. Schematic of a fabrication process of partial SJ structure by trench-filling epitaxial (TFE) growth method. The partial-SJ structure consists of the SJ-drift part and n-type buffer layer (n1>n2).

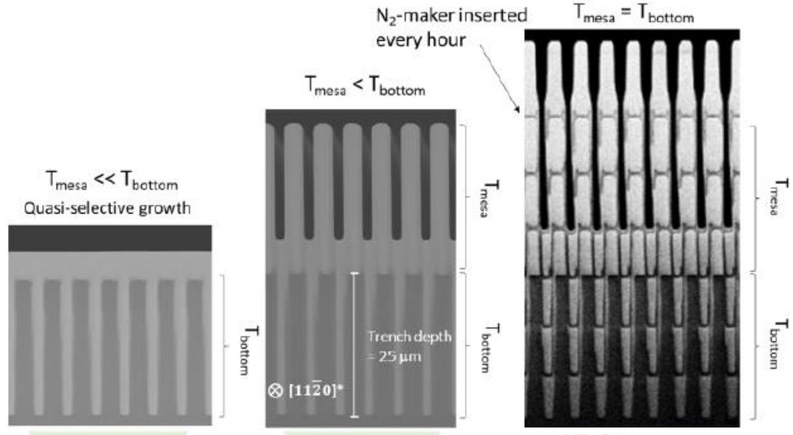


Figure 2. Cross-sectional SEM images of S
different TFE growth conditions in terms of

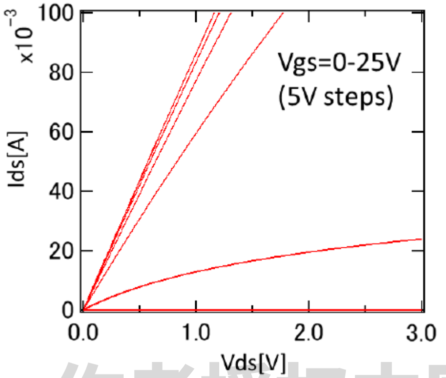


Figure 8. Ids-Vds of SJ MOSFET at RT.

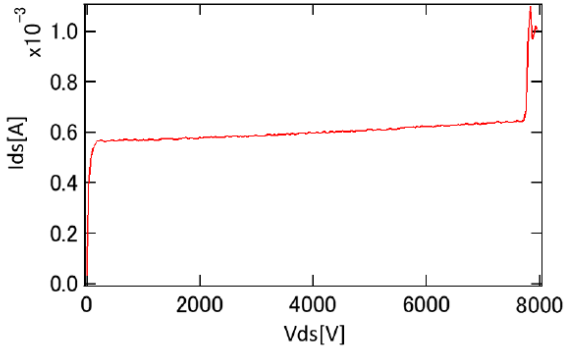


Figure 9. Blocking characteristics of SJ MOSFET (not removing voids by cleavage).

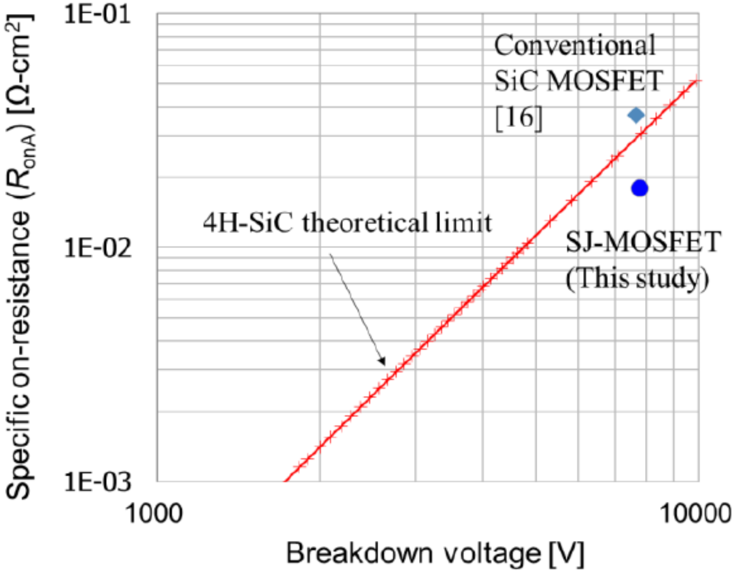


Figure 10. Trade-off relationship between specific resistivity of drift layer and breakdown voltage. Blue circle corresponds to this study.

R. Kosugi, et. al., "Breaking the Theoretical Limit of 6.5kV-Class 4H-SiC Superjunction (SJ) MOSFETs by Trench-Filling Epitaxial Growth," Proc. of ISPSD 2019, pp. 39-42, May 2019.

1.2kV SiC SuperjunctionTrench MOSFET

☐ Dynamic operations of rugged SiC Superjunction MOSFET with BVdss=1.6kV.

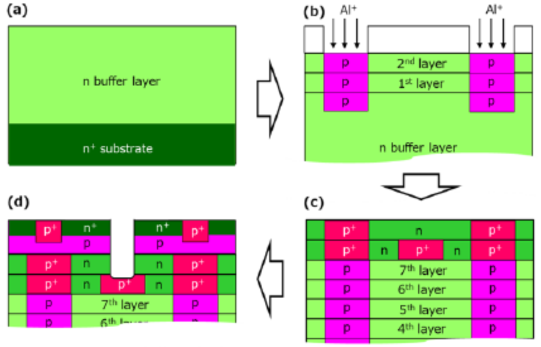


Fig. 4. Fabrication flow of SiC SJ-UMOSFET through multi-epitaxial growth method.

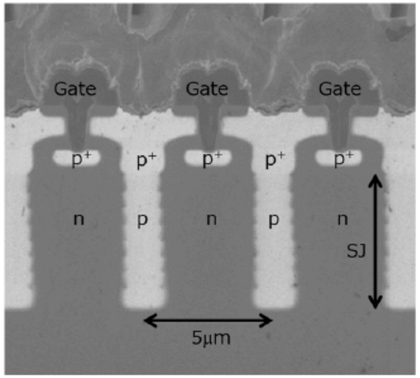


Fig. 5. SEM image of developed 1.2-kV class SiC SJ-UMOSFET.

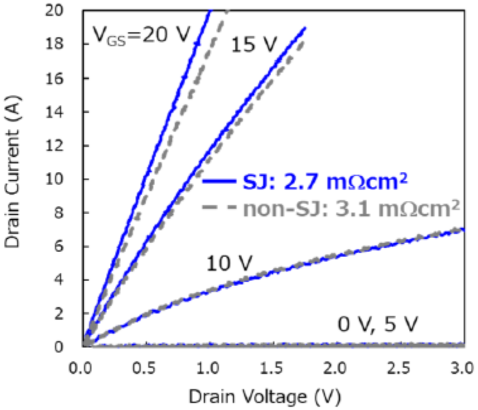


Fig. 6. Typical output characteristics of SJ- and non-SJ-UMOSFET. The RonA was measured at a drain current of 18 A and a gate voltage of 20 V.

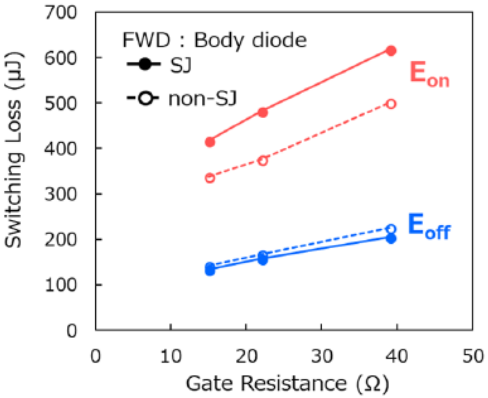


Fig. 16. Gate resistance dependences of switching energies for turn-on and turn-off of SJ- and non-SJ-UMOSFET with internal body diode as freewheeling diode.

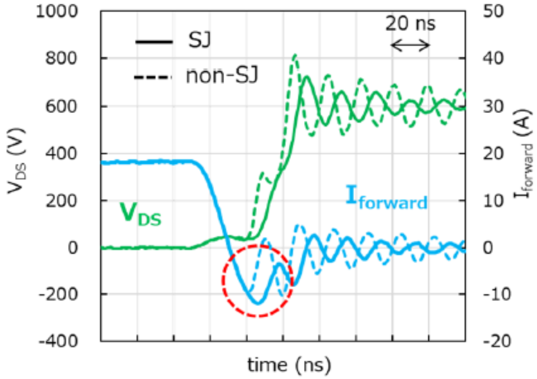


Fig. 17. Reverse recovery waveform of the body diode as freewheeling diode in SJ- and non-SJ-UMOSFET.

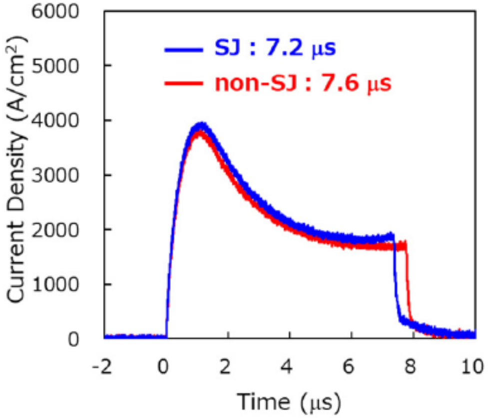


Fig. 18. Short circuit waveforms of SJ- and non-SJ-UMOSFET.

S. Harada, et. al., "First Demonstration of Dynamic Characteristics for SiC Superjunction MOSFET Realized Using Multi-epitaxial Growth Method," Tech. Digest of IEDM 2018, pp. 181-184, Dec. 2018.

1.2kV SiC SuperjunctionTrench MOSFET

- **Dramatic reduction of on-resistance at elevated temperature and low-loss and rugged reverse recovery of SiC Superjunction MOSFET with BVdss=1.6kV.**

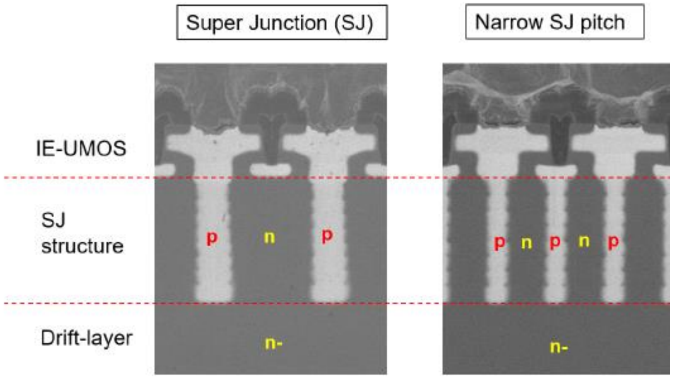


Fig. 2 SEM micrographs of fabricated SJ MOSFETs

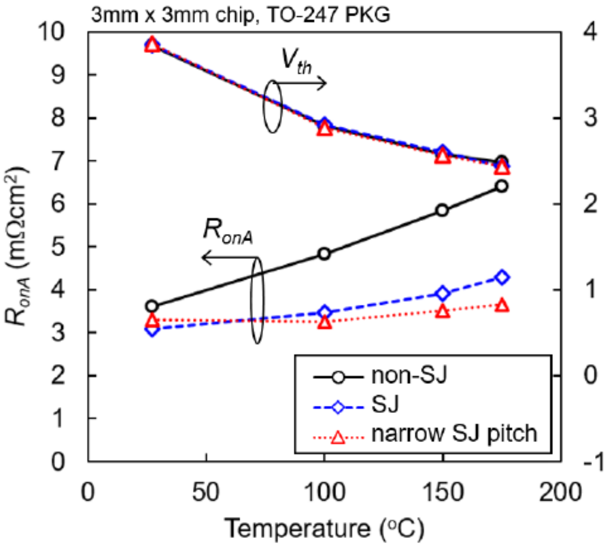


Fig. 4 Temperature dependency of R_{onA} and V_{th}

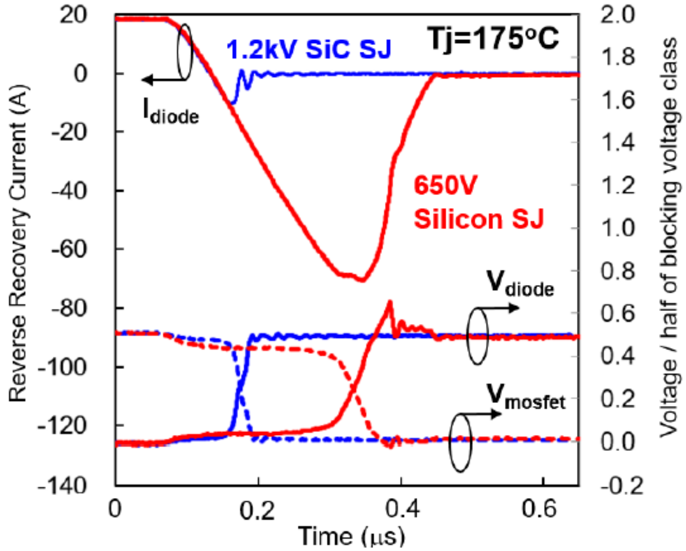


Fig. 15 Reverse recovery of the Si and SiC SJ devices

Y. Kobayashi, et. al., “High-temperature Performance of 1.2kV-class SiC Superjunction MOSFET,” Proc. of ISPSD 2019, pp. 31-34, May 2019.

0.63mΩcm^2 SiC Superjunction MOSFET

☐ **Extremely low specific on-resistance 0.63mΩcm^2/1170V close to SiC unipolar limit.**

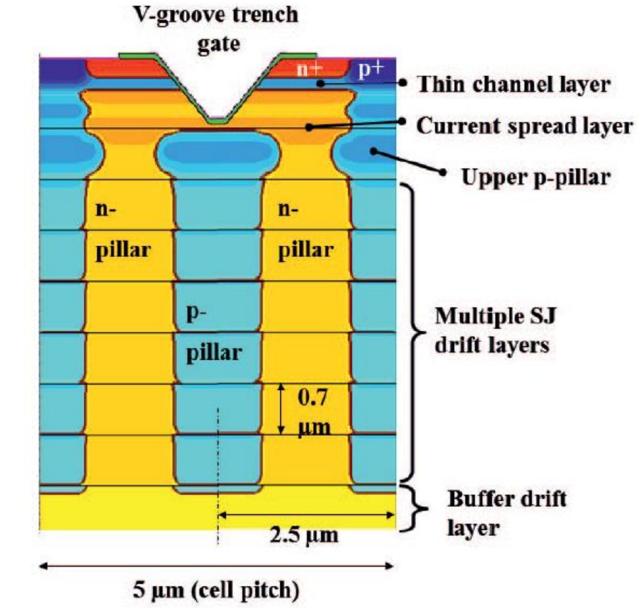


Fig. 1. A schematic cross section of the SJ-VMOSFET.

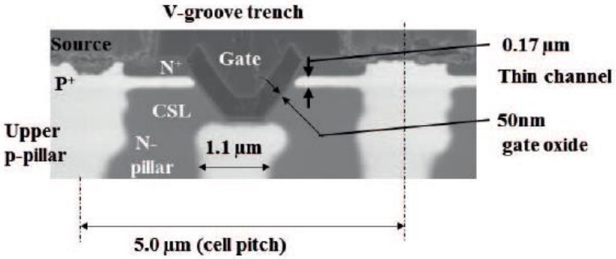


Fig.2. An SEM image of the fabricated SJ-VMOSFET with the ultra-thin channels.

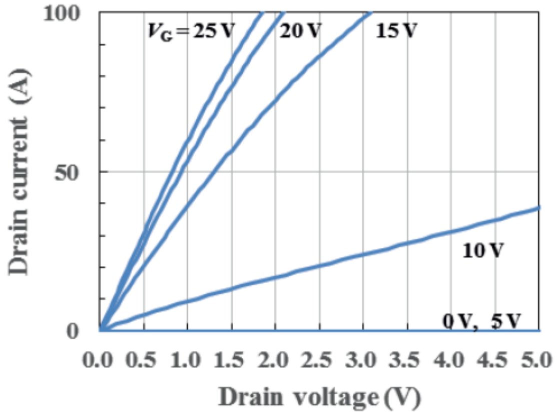


Fig. 4. Output characteristics of the SJ-VMOSFET with the active area of 0.0377cm^2.

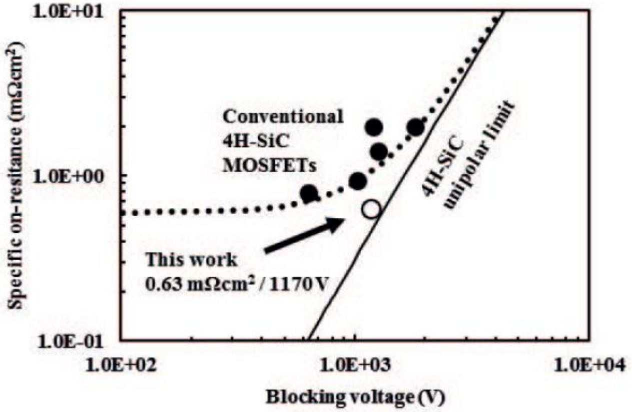


Fig. 8. Tradeoff relationship between $R_{on,\,sp}$ and B_V of 4H-SiC MOSFETs.

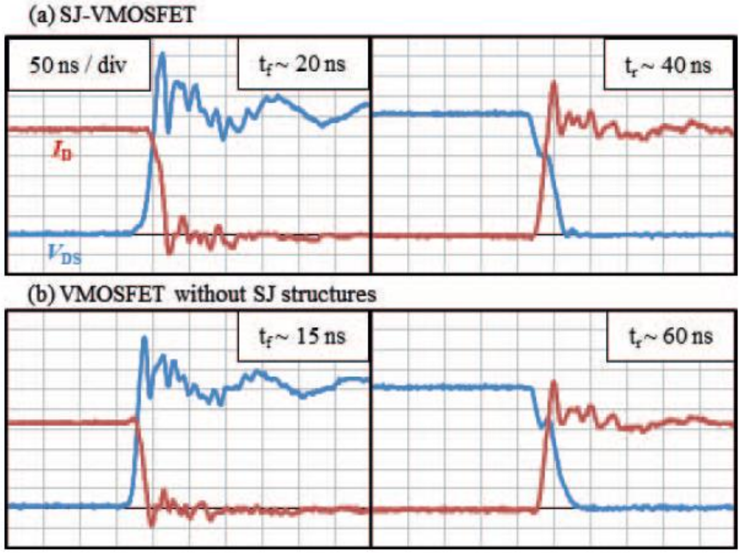


Fig. 11. Switching waveform comparison between the SJ-VMOSFET (a) and the VMOSFET without SJ structures (b).

T. Masuda, et. al., "0.63mΩcm^2/1170V 4H-SiC Superjunction V-Groove Trench MOSFET," Tech. Digest of IEDM 2018, pp. 177-180, Dec. 2018.

Latest Situation of SiC IGBT, Dec. 2018

□ 6kV 60A switching up to 250℃ by 8.0mmx8.0mm 16.5kV SiC IGBT.

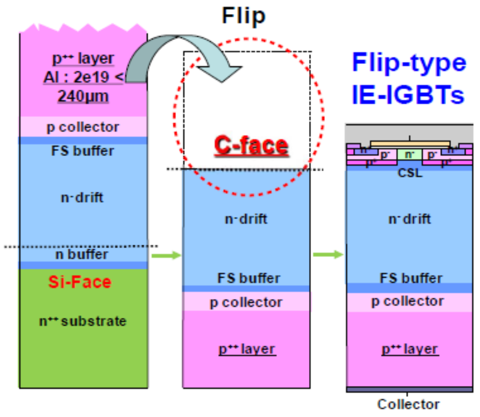


Fig. 11. Process flow of Flip-type IE-IGBT.

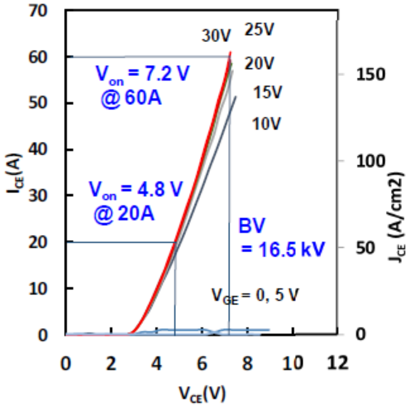


Fig. 12. On state characteristics of the 8 mm × 8 mm 16 kV IE-IGBT.

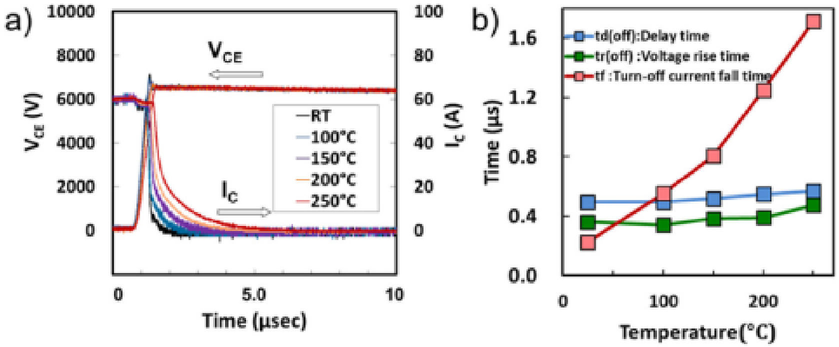


Fig. 13. a) Turn-off switching waveforms and b) Turn-off current fall time of the 8 mm × 8 mm IE-IGBTs.

□ 10kV 100A switching up to 200℃ by 4X 5.3mmx5.3mm 16.5kV SiC IGBT.

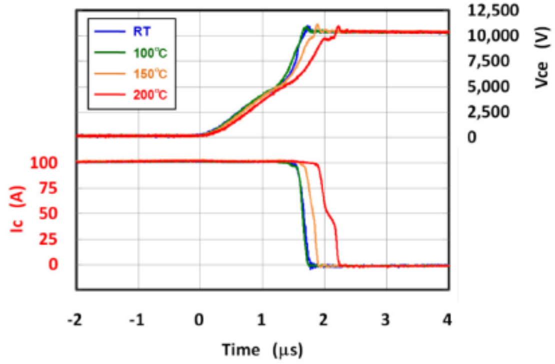


Fig. 14. Demonstration of 1 MVA turn-off switching wave form of four IGBTs parallel in one module.

□ New project: 20kV-class SiC IGBT under development.

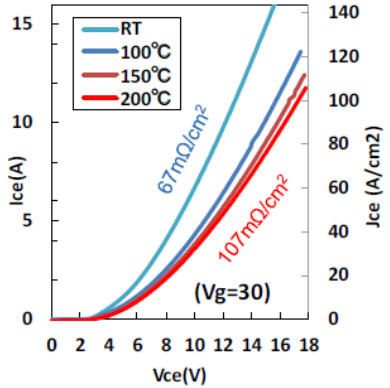


Fig. 15. On-state characteristics of the 20-kV class IE-IGBTs.

Y. Yonezawa, et. al., "Progress in High and Ultrahigh Voltage Silicon Carbide Device Technology," Tech. Digest of IEDM 2018, pp. 444-447, Dec. 2018.

Latest Situation of SiC IGBT, Sep. 2019

☐ **26.8kV, 36.9mΩcm²@100A/cm², Vce(sat)=8.2V@100A/cm², SiC IGBT demonstrated.**

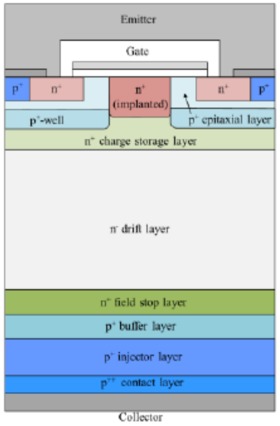


Fig. 1. Schematic cross-section of n-IE-IGBTs.

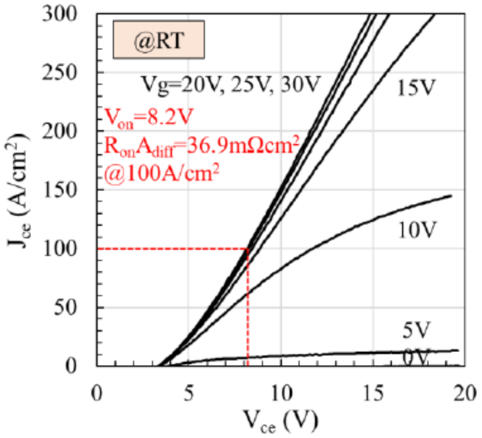


Fig. 2. On-state I-V characteristics of the n-IE-IGBT at room temperature.

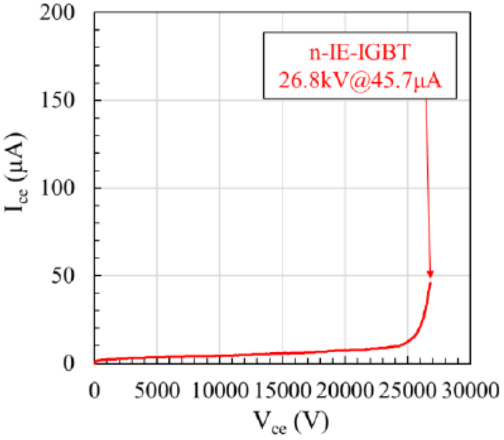


Fig. 3. Blocking characteristics of the n-IE-IGBT.

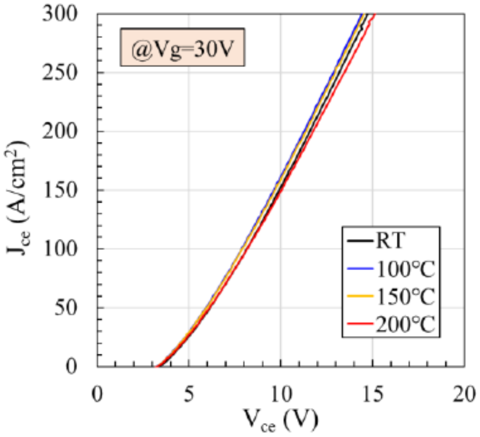
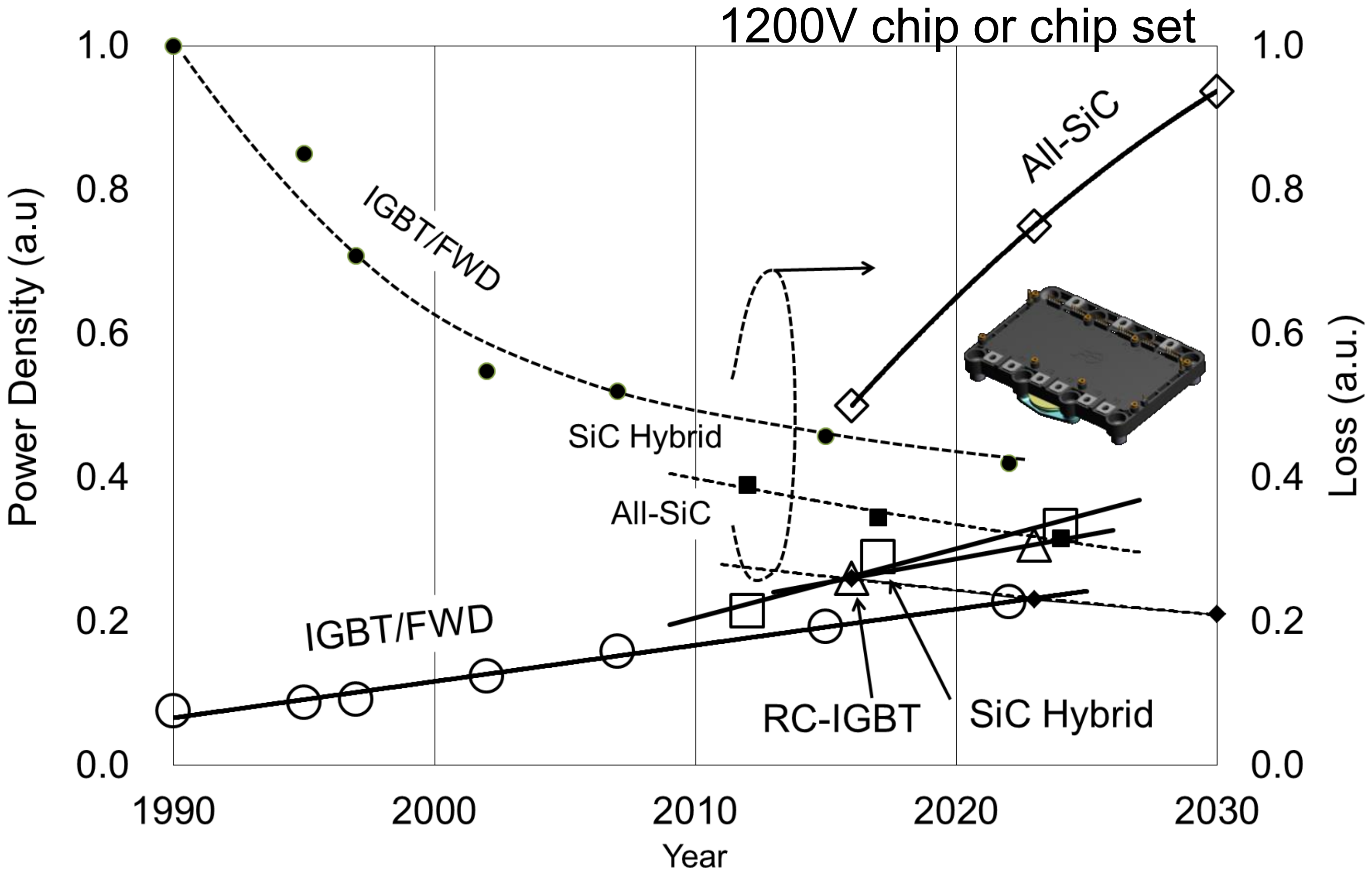


Fig. 4. Temperature dependence of on-state I-V characteristics of the n-IE-IGBT at the gate voltage of 30V.

A. Koyama, et. al., “20kV-class Ultra-High Voltage 4H-SiC n-IE-IGBTs,” Abstructs of ICSCRM 2019, Fr-2A-05, Sep. 2019.

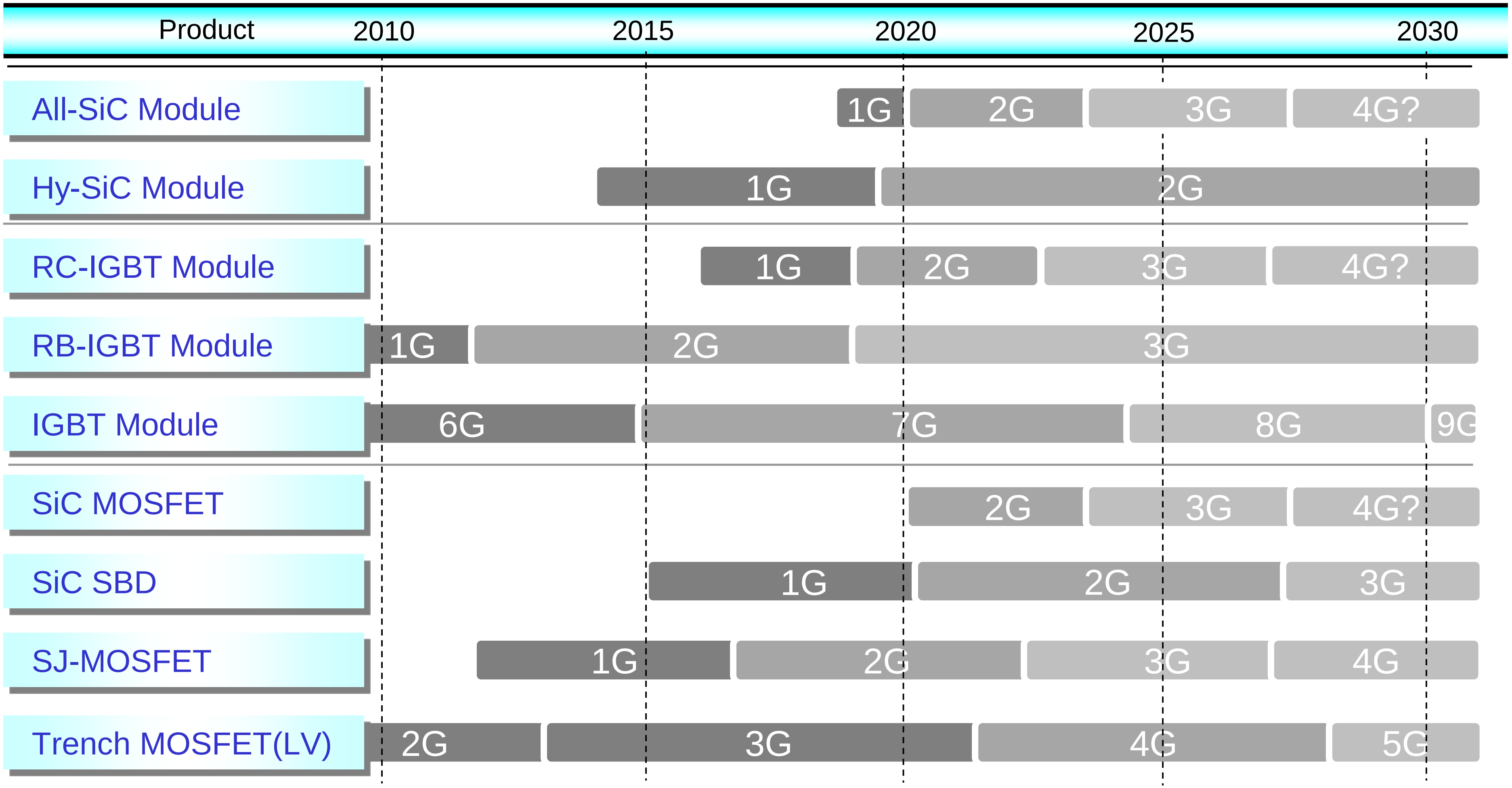
□ Conclusions

Trend and Forecast of Power Density and Loss of Power Device Chips



Power Density: **Power Rating (Voltage x Current) / Total Chip Area**
Loss: **Estimated Total Power Dissipation in 400VAC General Purpose Inverter**

Fuji’s Roadmap of Power Semiconductor Devices



Indication by chip generation

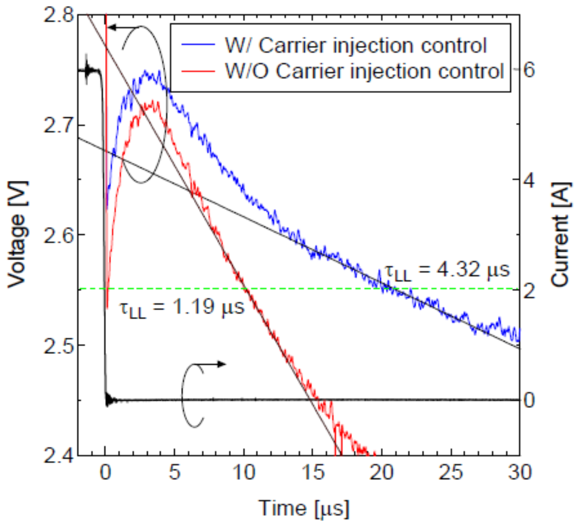
Thank you!

Acknowledgment

Some part of this work has been implemented under a joint research project of Tsukuba Power Electronics Constellations (TPEC).

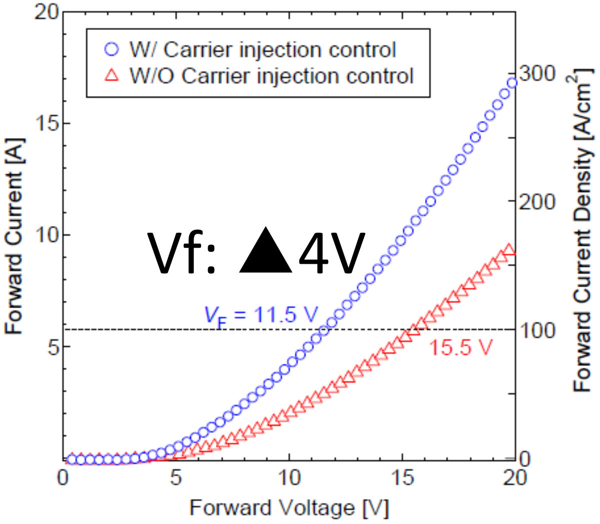
27.5kV PiN Diode with Low Vf

- The low-level carrier lifetimes (t_{LL}) of the PiN diodes were calculated from the OCVD waveform slopes at 2.55 V, being 4.32 and 1.19 μs for the diodes fabricated with and without carrier injection control, respectively
- By introducing carrier injection control, the **Vf of fabricated PiN diode decreased from 15.5 to 11.5 V**.
- The VB of the fabricated PiN diode was 27.5 kV, which is the highest yet reported for 20-A 4H-SiC PiN diode.

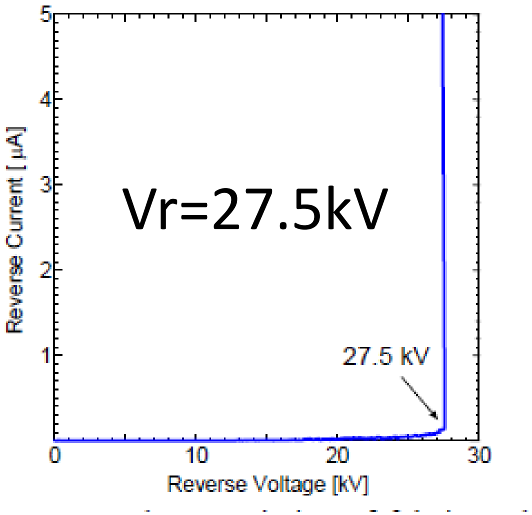


OCVD waveforms of fabricated PIN diodes

OCVD:Open Circuit Voltage Decay



Forward Characteristics of Fabricated PiN Diodes

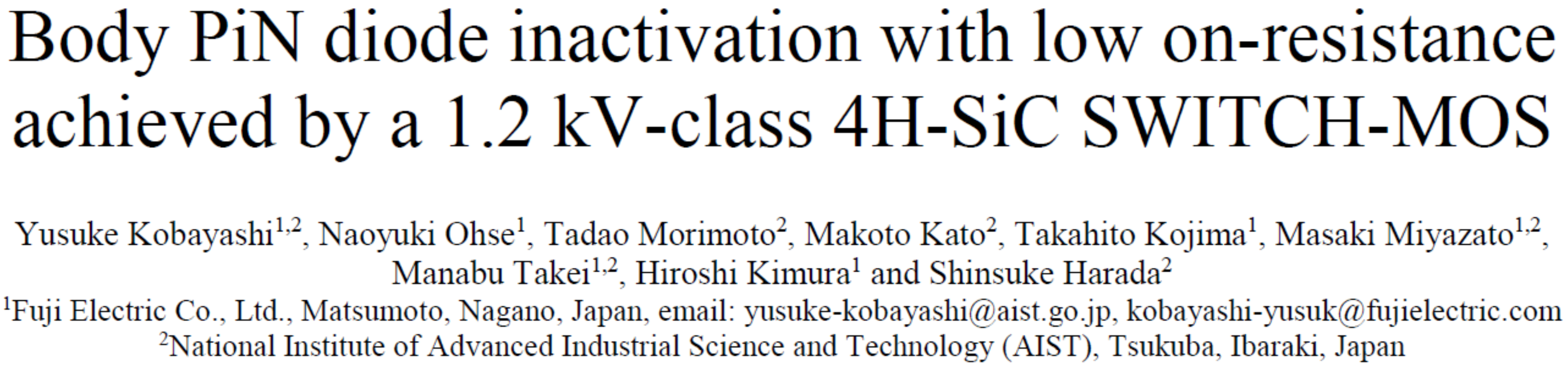


Reverse Characteristics of Fabricated PiN Diode

K.Nakayama et.al, WE.02a.04, ECSCRM 2018, Birmingham, UK, Wed. Sep. 5, 2018

This work was supported by SIP and a collaboration with AIST, Fuji Electric, New Japan Radio, Mitsubishi Electric, and Kyoto Univ.

SBD-Integrated SiC Trench MOSFET



Body PiN diode inactivation with low on-resistance achieved by a 1.2 kV-class 4H-SiC SWITCH-MOS

Yusuke Kobayashi[1,2], Naoyuki Ohse[1], Tadao Morimoto[2], Makoto Kato[2], Takahito Kojima[1], Masaki Miyazato[1,2],
Manabu Takei[1,2], Hiroshi Kimura[1] and Shinsuke Harada[2]
[1]Fuji Electric Co., Ltd., Matsumoto, Nagano, Japan, email: yusuke-kobayashi@aist.go.jp, kobayashi-yusuk@fujielectric.com
[2]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan

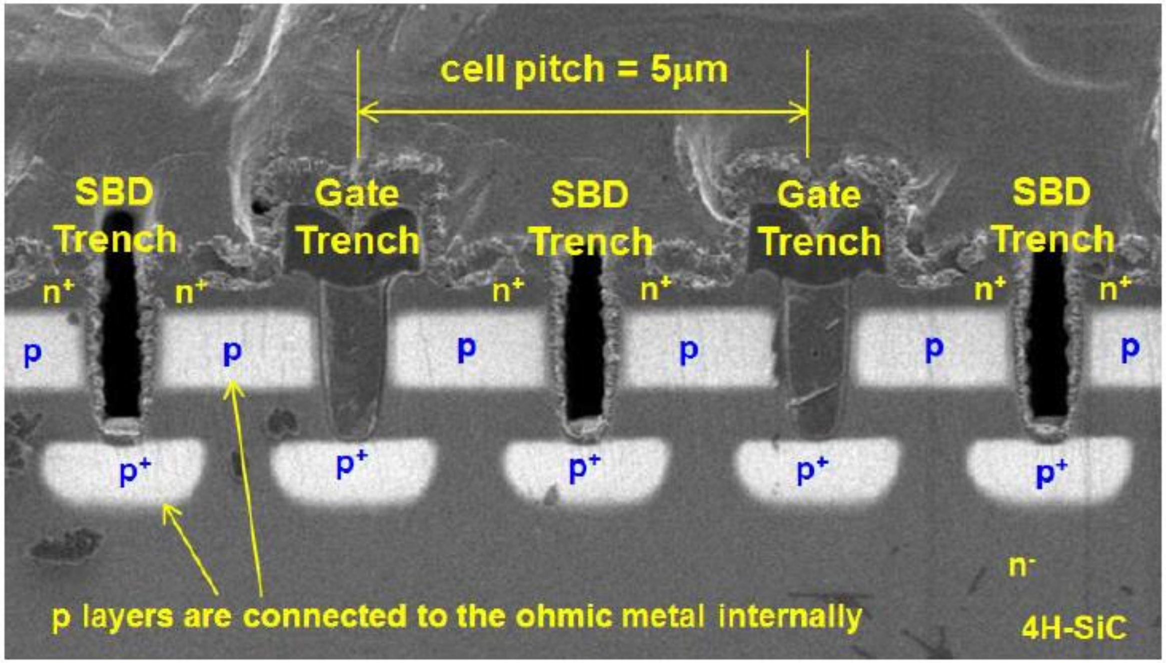


Fig. 8. Cross-sectional SEM image of the SWITCH-MOS with a 5 um cell pitch

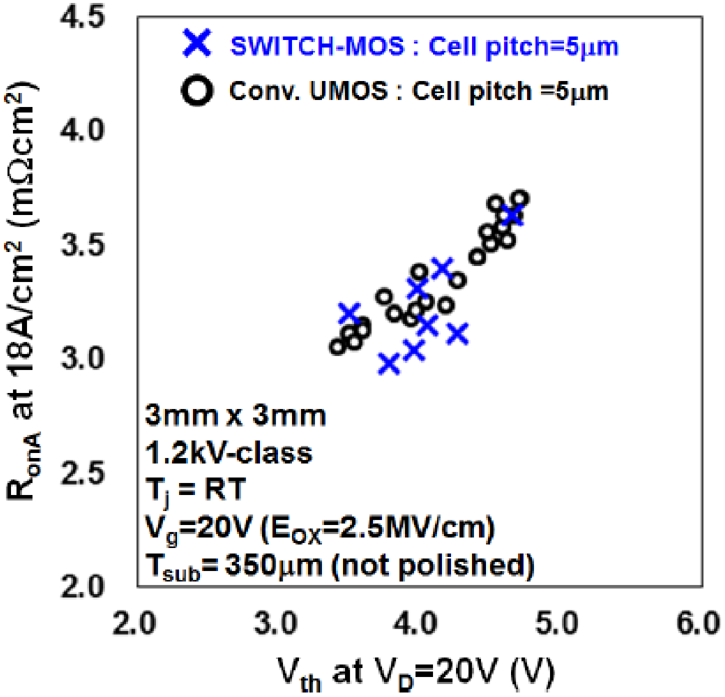


Fig. 10. R_{onA}-V_{th} trade-off in the SWITCH-MOS and conventional UMOS

Y. Kobayashi, et. al., Tech. Digest of IEDM 2017, pp. 211-214, Dec. 2017.

SBD-Integrated SiC Trench MOSFET

- No degradation of Ron or Vf up to 1500A/cm^2 reverse current conduction

1200V Device

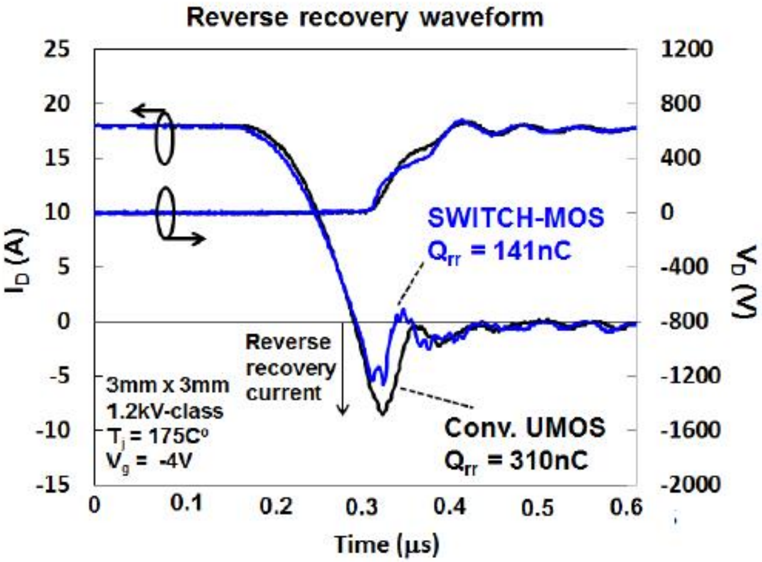


Fig. 13. Reverse recovery waveform of the body diode as a freewheeling diode in the SWITCH-MOS and conventional UMOS

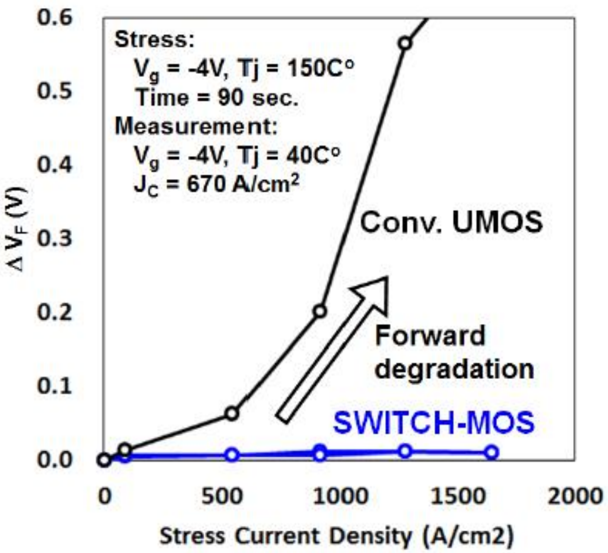


Fig. 14. Forward degradation as a function of forward current stress in the SWITCH-MOS and conventional UMOS

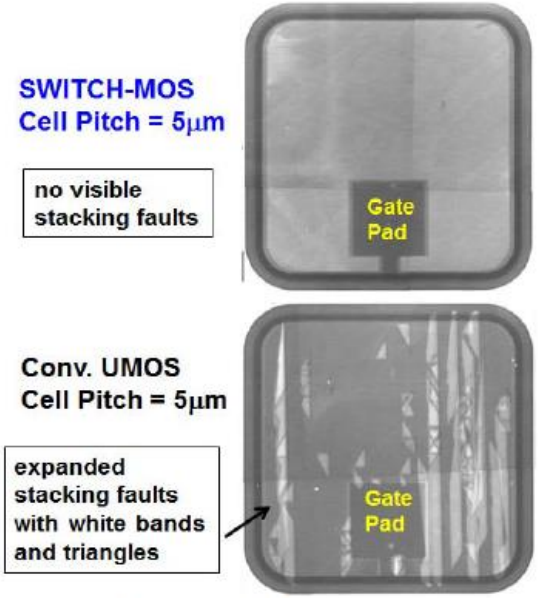


Fig. 15. Photoluminescence mapping images of stacking faults after stress of 1640 A/cm^2 for 90 seconds

Y. Kobayashi, et. al., Tech. Digest of IEDM 2017, pp. 211-214, Dec. 2017.

Low On-Resistance SiC Trench MOSFET

- The **halo implanted** high acceptor concentration region behind the channel blocks the penetration of the depletion region into the p-base. Since the short channel effect is suppressed without increasing the acceptor concentration in the channel, high channel mobility is maintained by low acceptor concentration.
- **Low RonA of 2.0 mΩcm^2 with high Vth of 4V achieved on the 1.2kV MOSFET.**

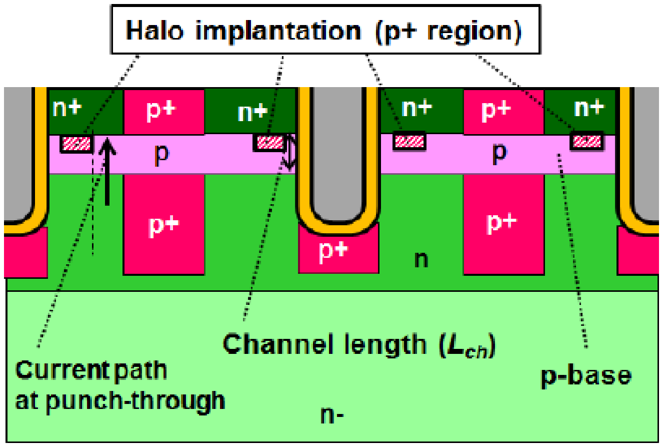


Fig. 1. Schematic cross-section of the halo implanted 4H-SiC IE-UMOS

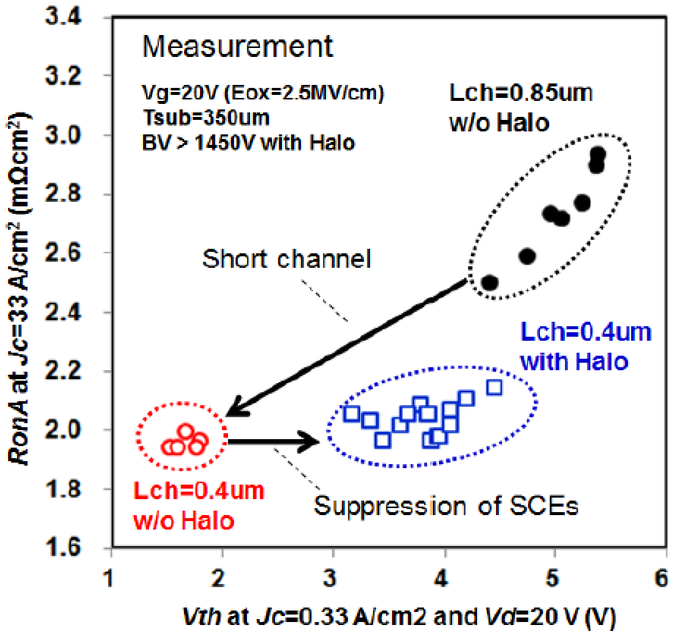
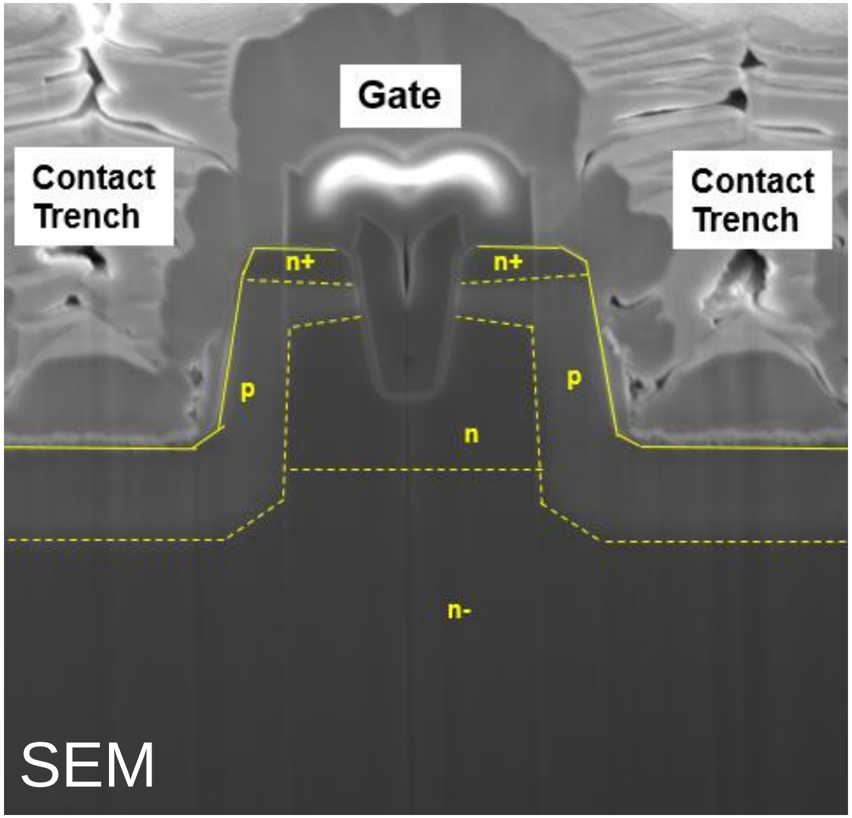


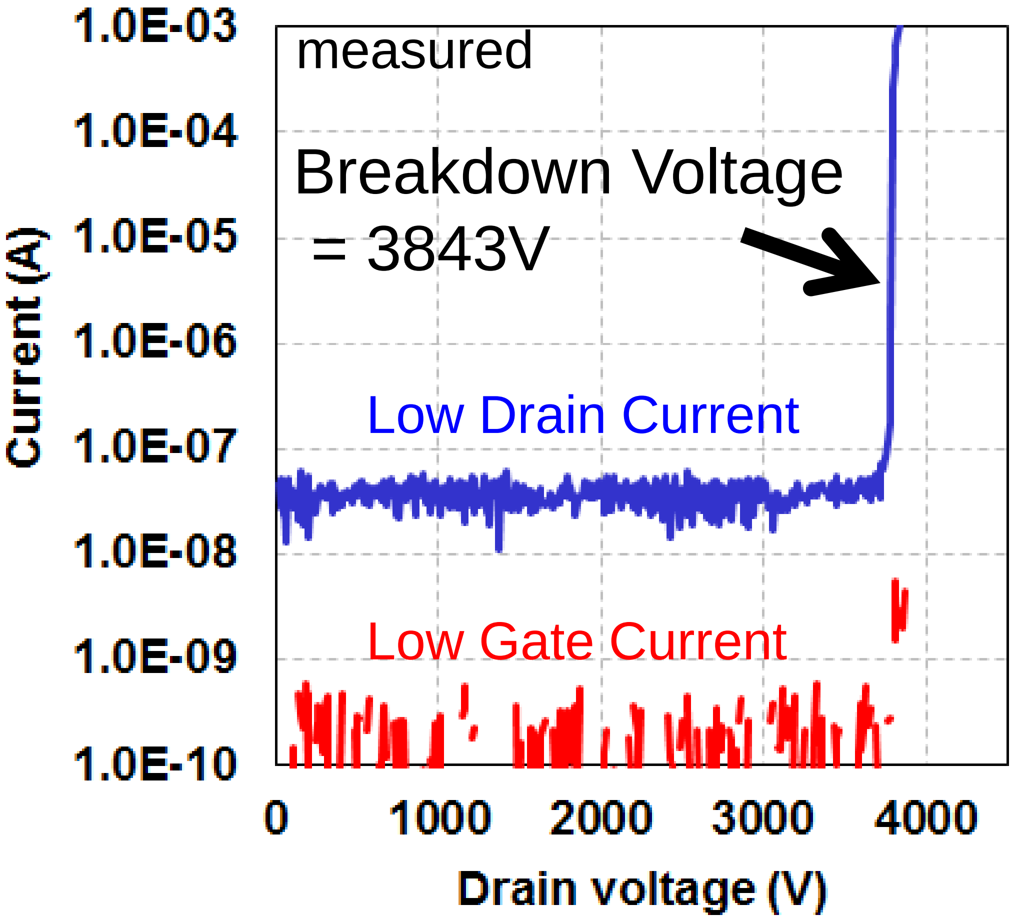
Fig. 4. Trade-off between R_{onA} and V_{th} in the fabricated IE-UMOS, with and without halo implantation.

Y.Kobayashi et.al, FR.D2.1, ICSCRM 2017, Washington, DC, USA, Fri. Sep. 22, 2017

This work has been implemented under a joint research project of Tsukuba Power Electronics Constellations (TPEC)

3.3kV SiC Trench MOSFET





Break down voltage of 3843V was achieved with small gate current

[Ref.] Y. Kobayashi, et. al., ICSCRM, 2015

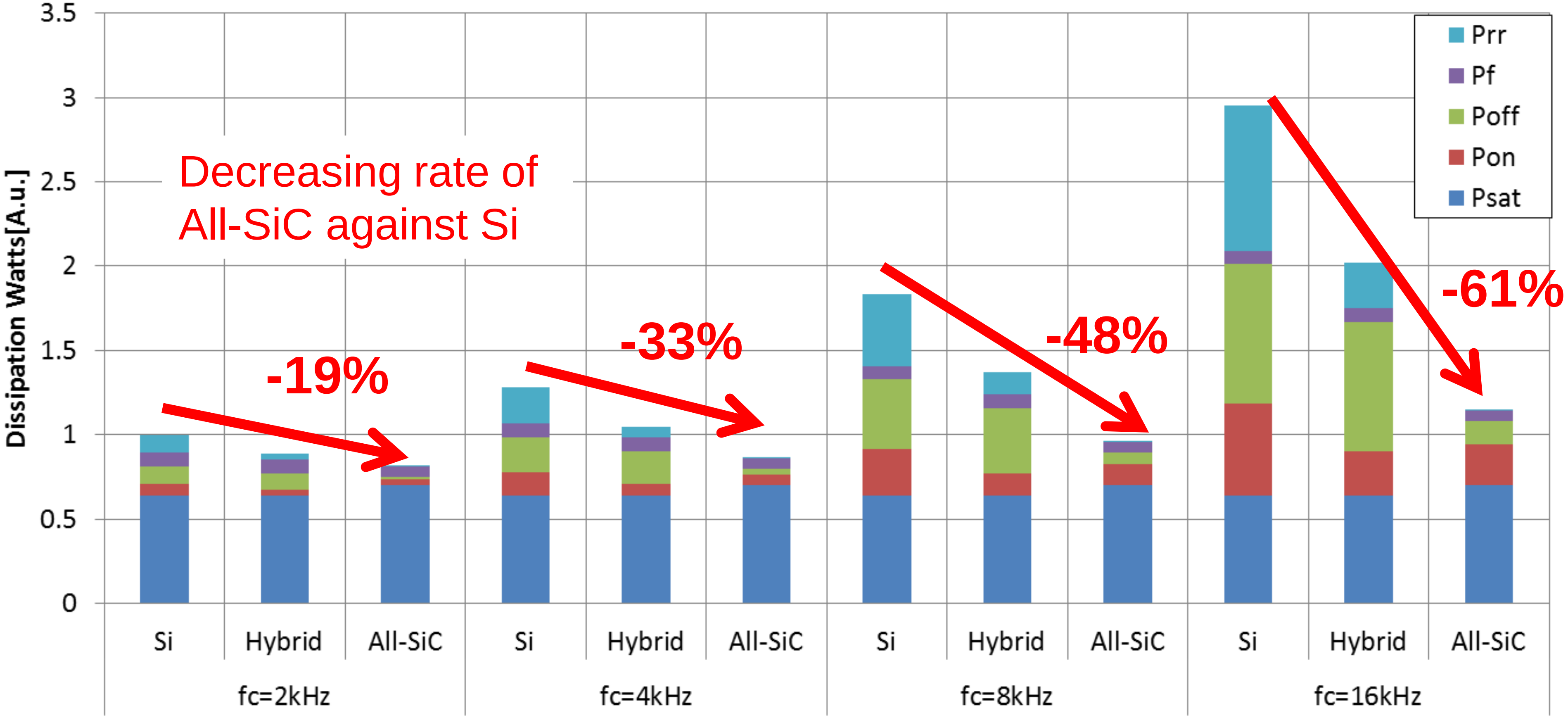
□ Comparison of Si, Hybrid-SiC, and All-SiC Modules

Loss Comparison IGBT/Hybrid-SiC/All-SiC

[Calc. condition]

fc=2 ~16kHz,Vcc=600V, Io=1/2rated, λ=1.0, fo=50Hz, cosΦ=0.9

1200V Device



Decreasing rate of All-SiC against Si

-19%

-33%

-48%

-61%

Loss Comparison IGBT/Hybrid-SiC/All-SiC

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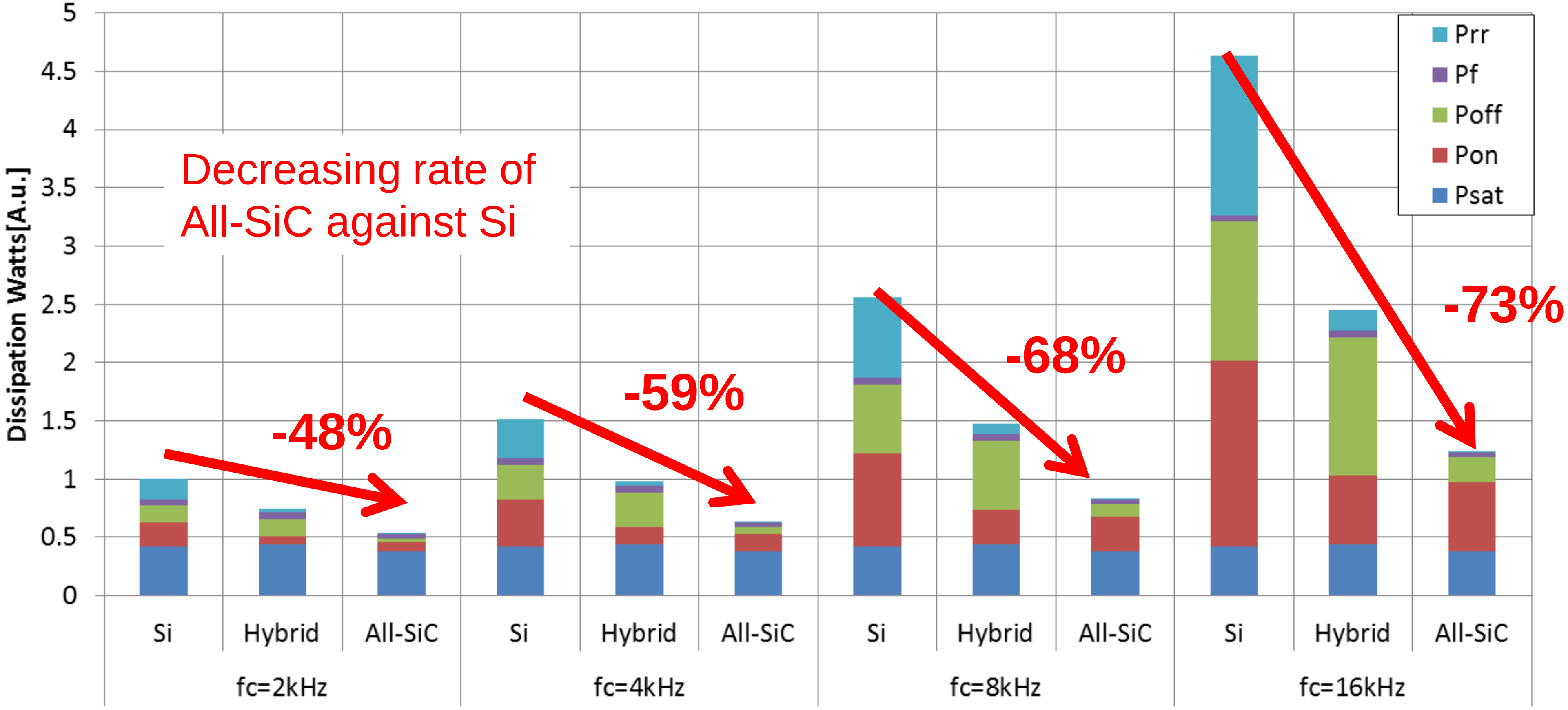
Innovating Energy Technology

[Calc. condition]

fc=2 ~16kHz, Vcc=900V, Io=1/2rated, λ=1.0, fo=50Hz, cosΦ=0.9

1700V Device

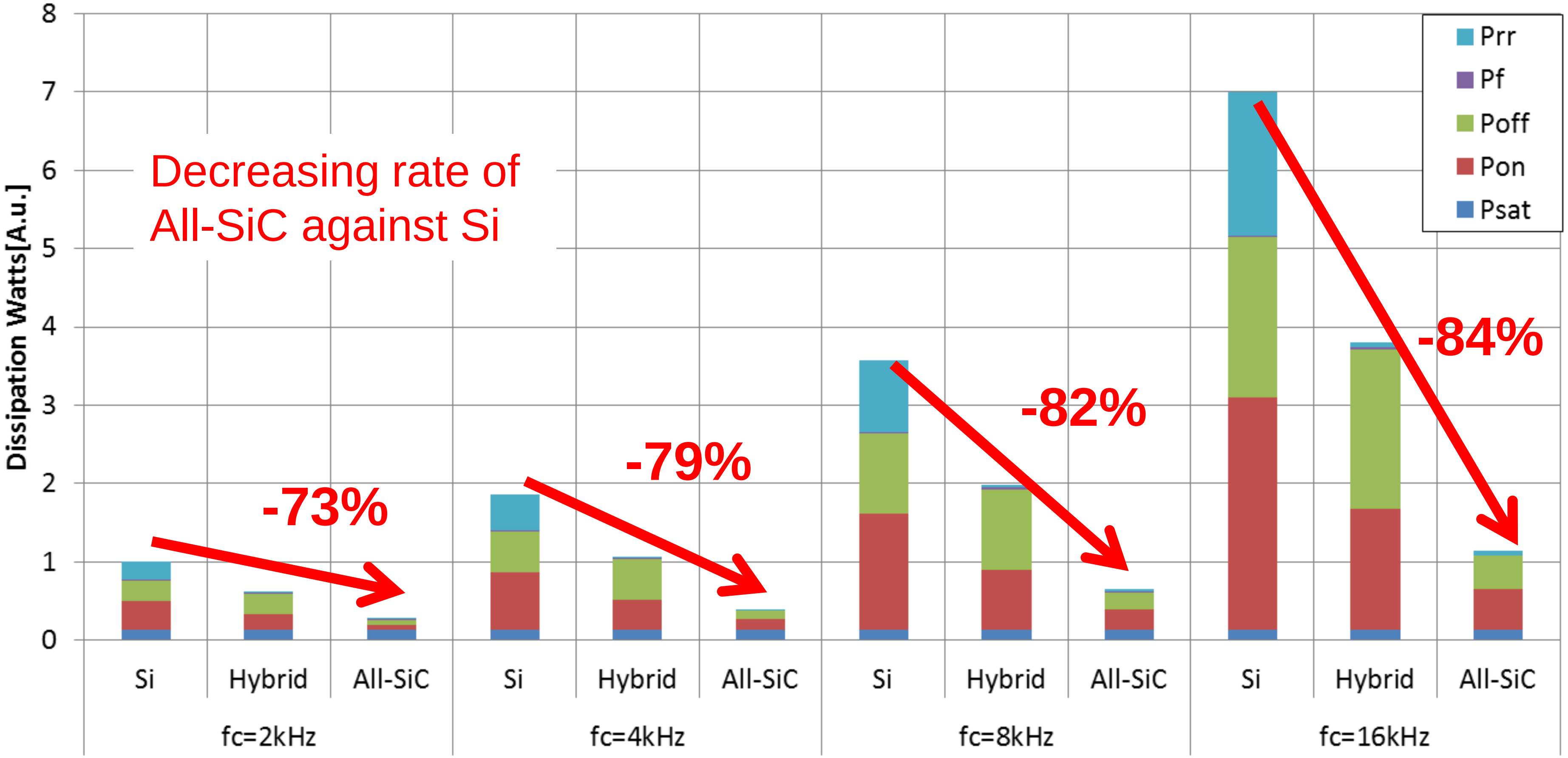


Loss Comparison IGBT/Hybrid-SiC/All-SiC

[Calc. condition]

fc=2 ~16kHz, Vcc=1800V, Io=1/2rated, λ=1.0, fo=50Hz, cosΦ=0.9

3300V Device



□ SiC-MOSFET

Electrical performance of All-SiC Module

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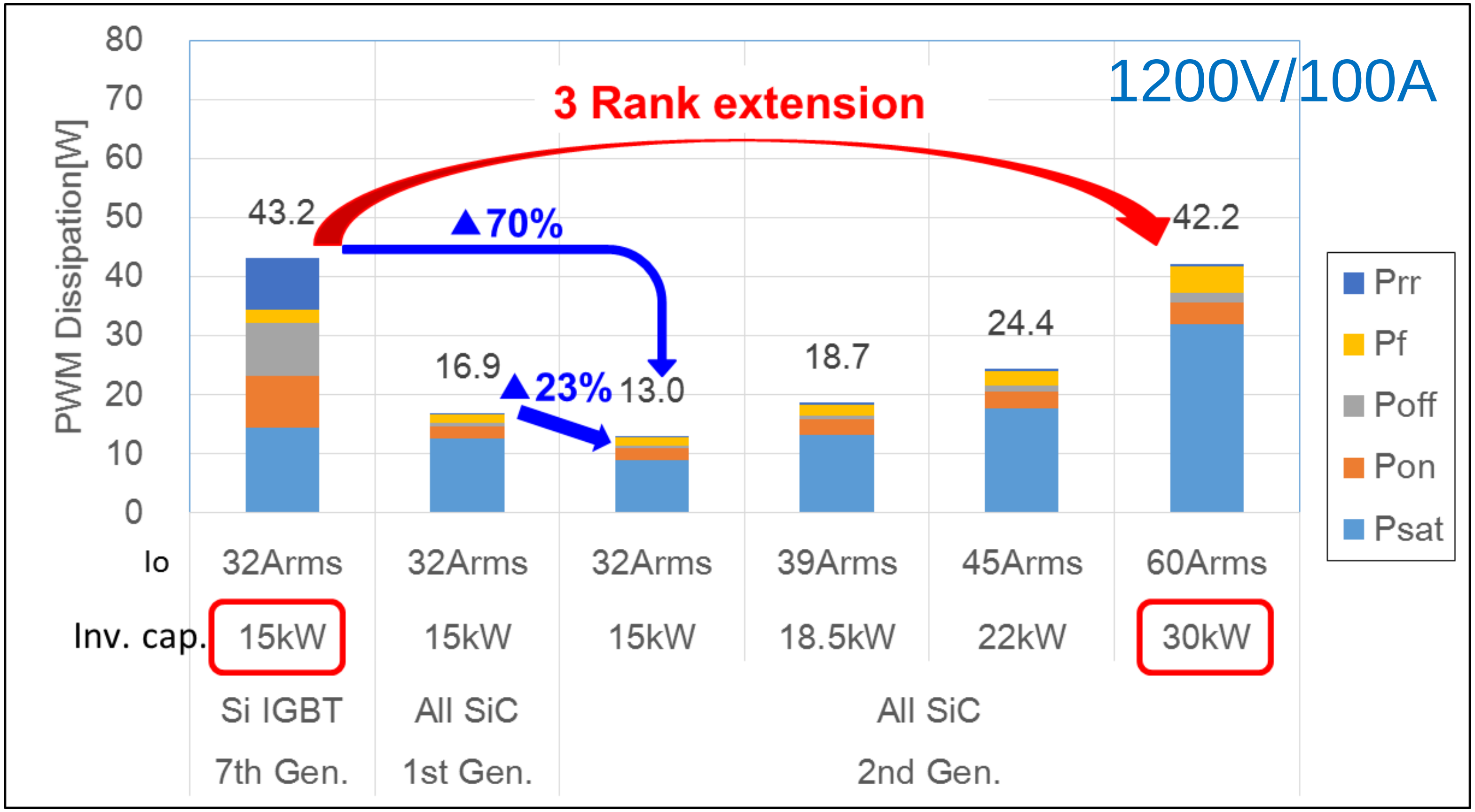
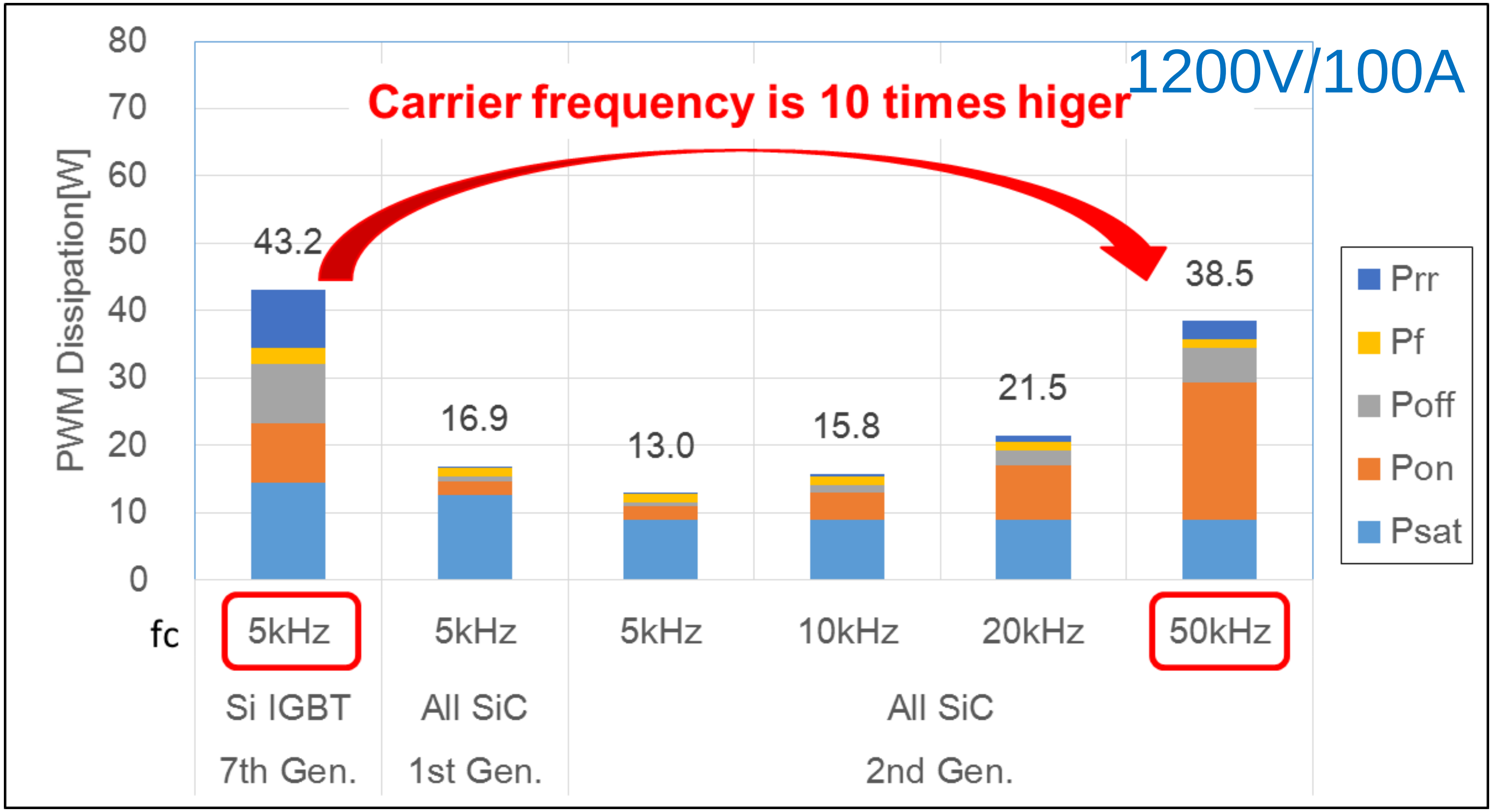
Innovating Energy Technology



The Io for the All-SiC module was raised from 32Arms to 60Arms under conditions that fc is 5 kHz, the dissipation loss was almost the same compared to 7th generation Si IGBT module.

→3 rank extension for inverter capacity can be realized by applying All-SiC module.

Electrical performance of All-SiC Module



The fc for the All-SiC module was raised from fc 5kHz to fc 50kHz under conditions that Io is 32 Arms, the dissipation loss was almost the same compared to 7th generation Si IGBT module.

→10times higher frequency can be realized by applying All-SiC module.

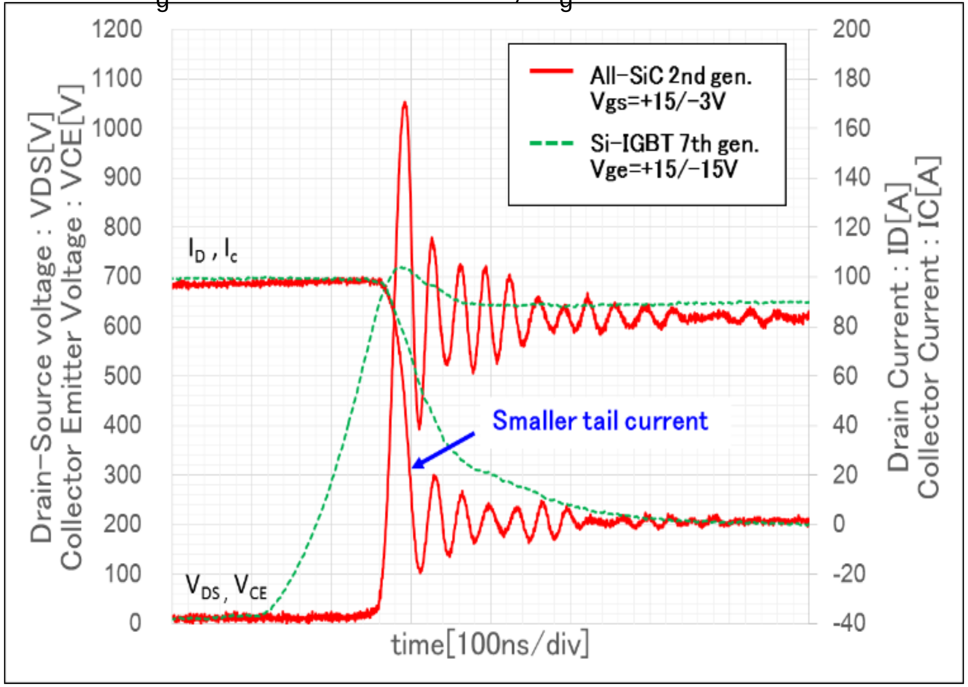
Electrical performance of All-SiC Module

Switching waveforms (1200V/100A)

Turn-off waveforms

[conditions] V_{cc}=600V, I_D=100A,

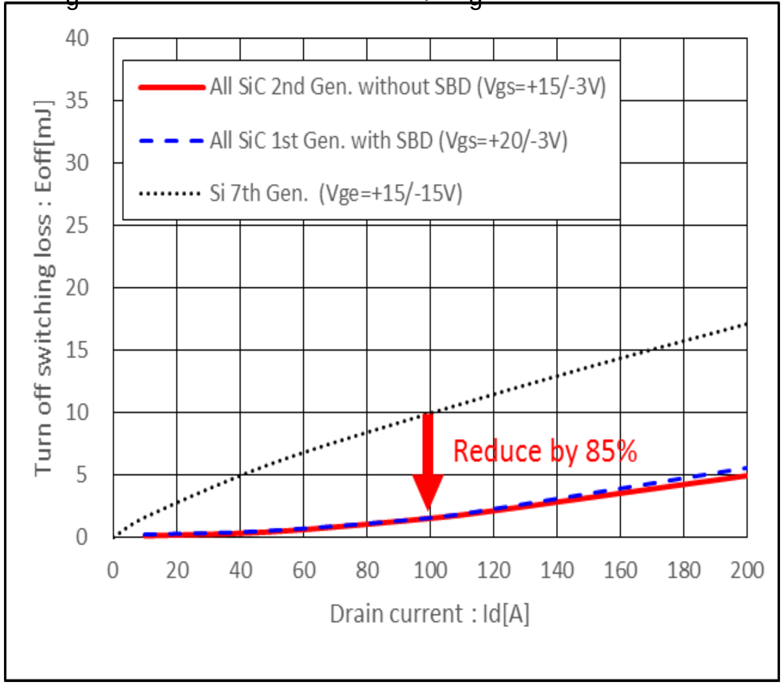
R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



Turn-off switching loss with Drain current

[conditions] V_{cc}=600V,

R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



The tail current of all-SiC module was reduced and the rising voltage was also faster compared to 7th generation Si IGBT module.

→ Eoff was reduced by 85%.

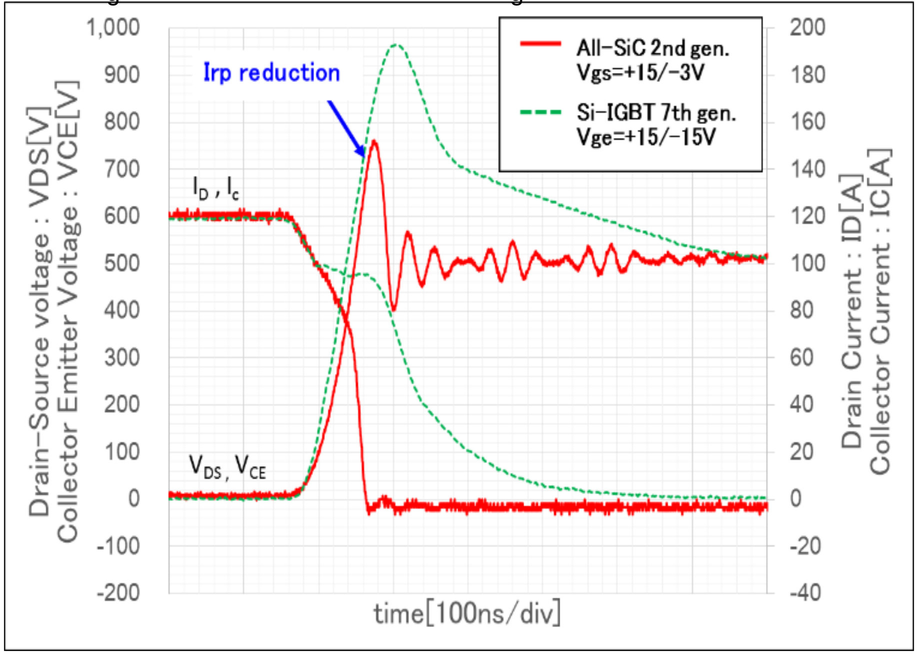
Electrical performance of All-SiC Module

Switching waveforms (1200V/100A)

Turn-on waveforms

[conditions] V_{cc}=600V, I_D=100A,

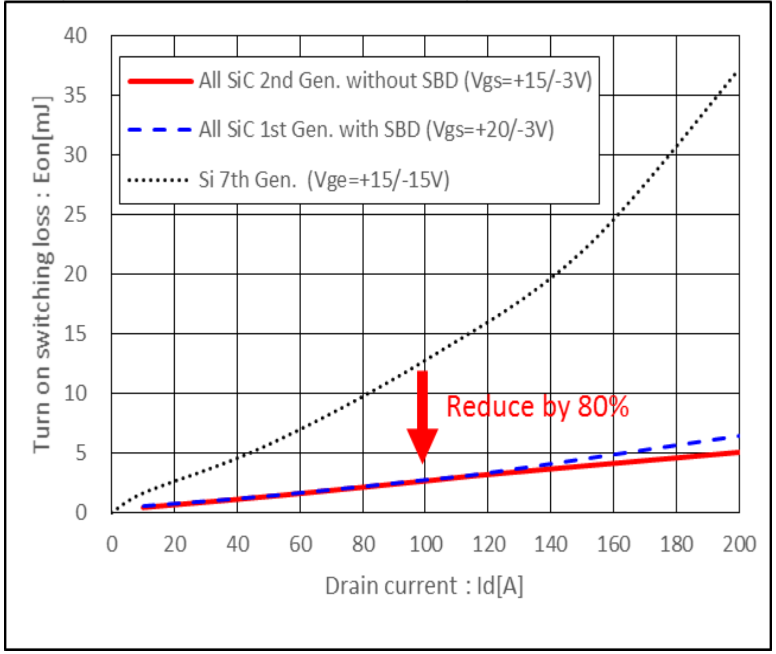
R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



Turn-on switching loss with Drain current

[conditions] V_{cc}=600V,

R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



The peak current at turn on of the all-SiC module was reduced compared to 7th generation Si IGBT module.

→ Eon was reduced by 80%.

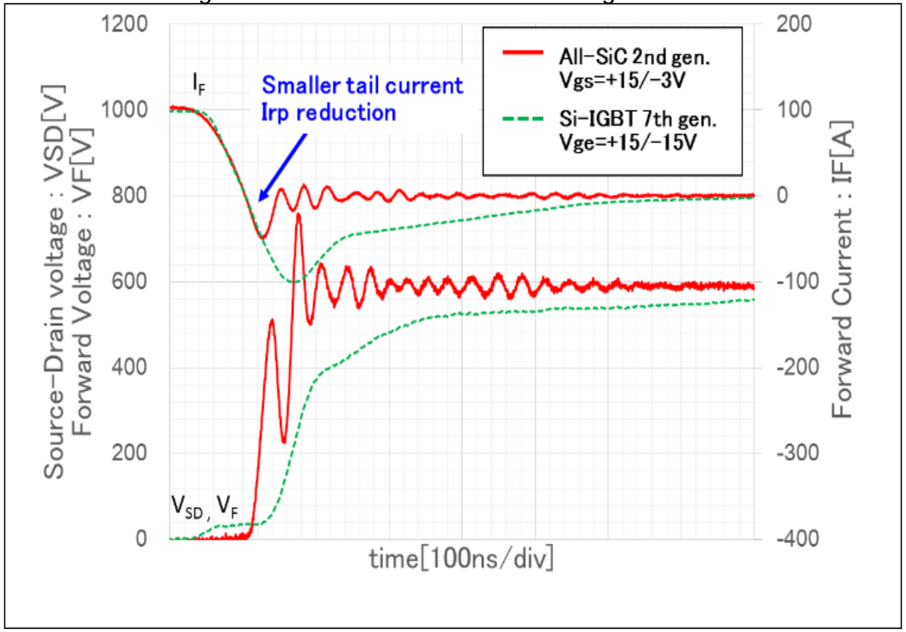
Electrical performance of All-SiC Module

Switching waveforms (1200V/100A)

Reverse recovery waveforms

[conditions] V_{cc}=600V, I_D=100A,

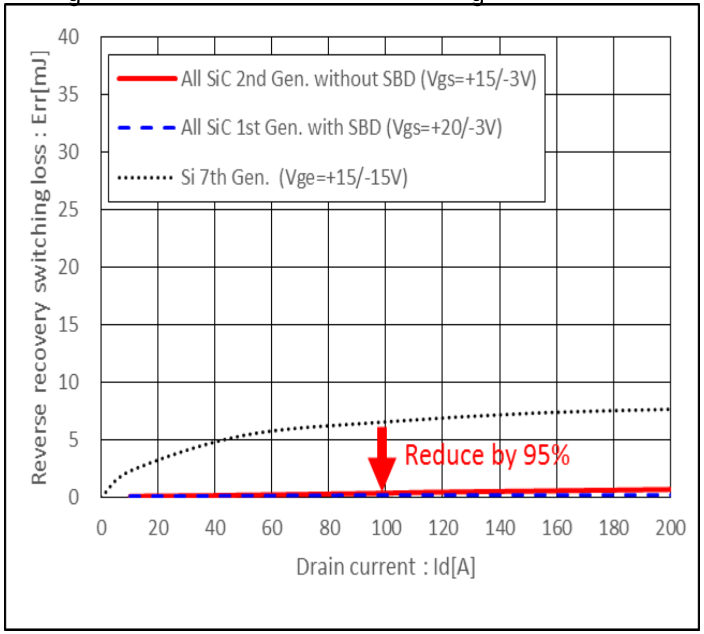
R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



Reverse recovery switching loss with Drain current

[conditions] V_{cc}=600V,

R_g=5.1Ω for Si 7th Gen., R_g=+27/-15Ω for All SiC



The tail current of all-SiC module was reduced compared to the 7th generation Si IGBT module.

→ Err was reduced by 95%.

Electrical performance of All-SiC Module

Comparison of switching losses (1200V/100A)

[conditions] V_{cc}=600V, I_D=100A, Tvj=175deg.C

R_g=5.1Ω, Vgs=±15V for Si 7th Gen., R_g=+27/-15Ω, Vgs=+15/-5V for All SiC

	E_{on} [mJ/pulse]	E_{off} [mJ/pulse]	E_{rr} [mJ/pulse]	E_{SW_total} [mJ/pulse]
All-SiC	2.7	1.5	0.4	4.5
7G-IGBT	12.8	9.9	6.5	29.2
Reduction rate	79%	85%	95%	85%

Total switching loss (Esw_total) was dramatically reduced by 85% compared to 7th generation Si module.

→Reduction of switching loss for the inverter is expected.

Output current of 1700V/300A All-SiC Module

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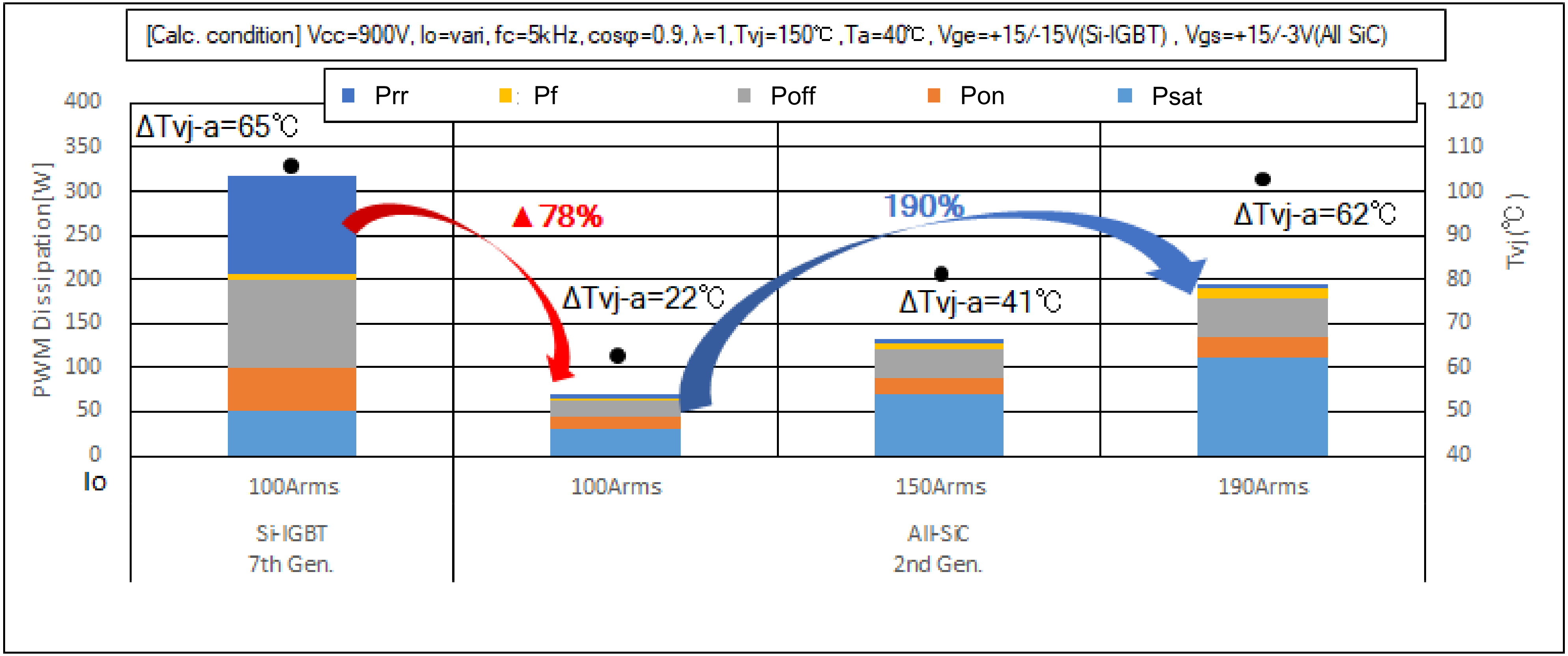

The Io for the All-SiC module was raised from 100Arms to 190Arms under conditions that fc is 5 kHz, the dissipation loss was almost the same compared to 7th generation Si IGBT module.

→Extension for inverter capacity can be realized by applying All-SiC module.

DC characteristics of 1700V/300A All-SiC Module

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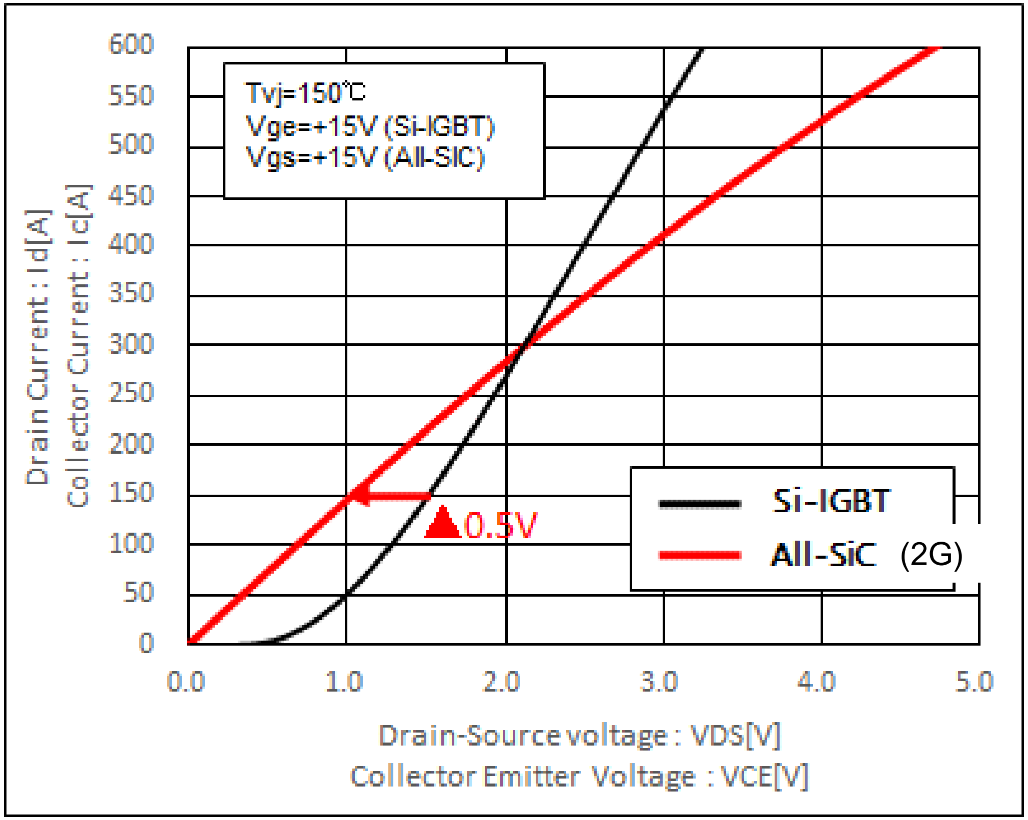
Innovating Energy Technology

Si 7th Gen./All-SiC2nd Gen. output characteristic



All-SiC output characteristic was improved!

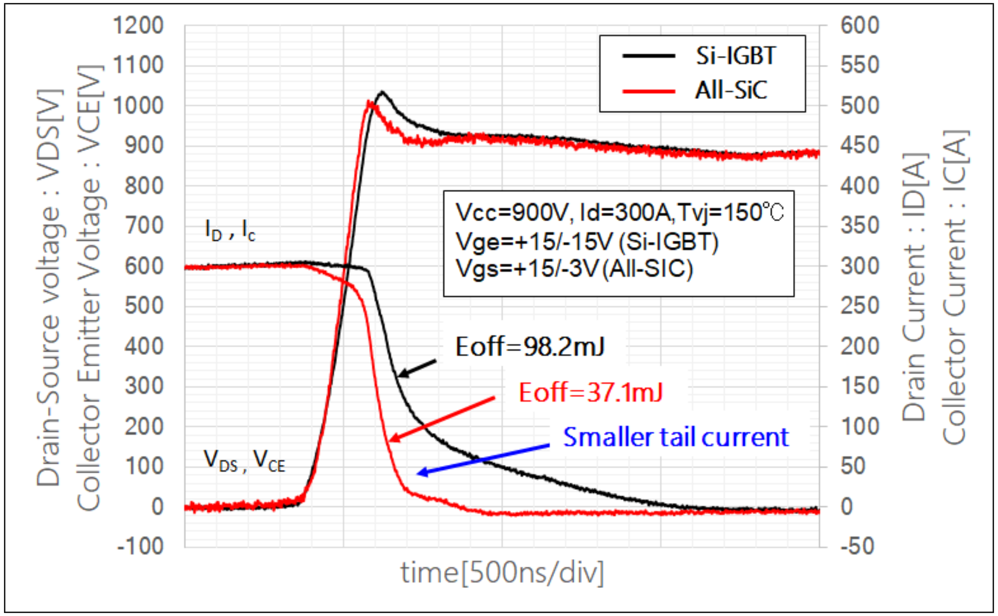
→The on-state voltage of all-SiC module was reduced under 300A.

Turn-off and -on characteristics of 1700V/300A All-SiC Module

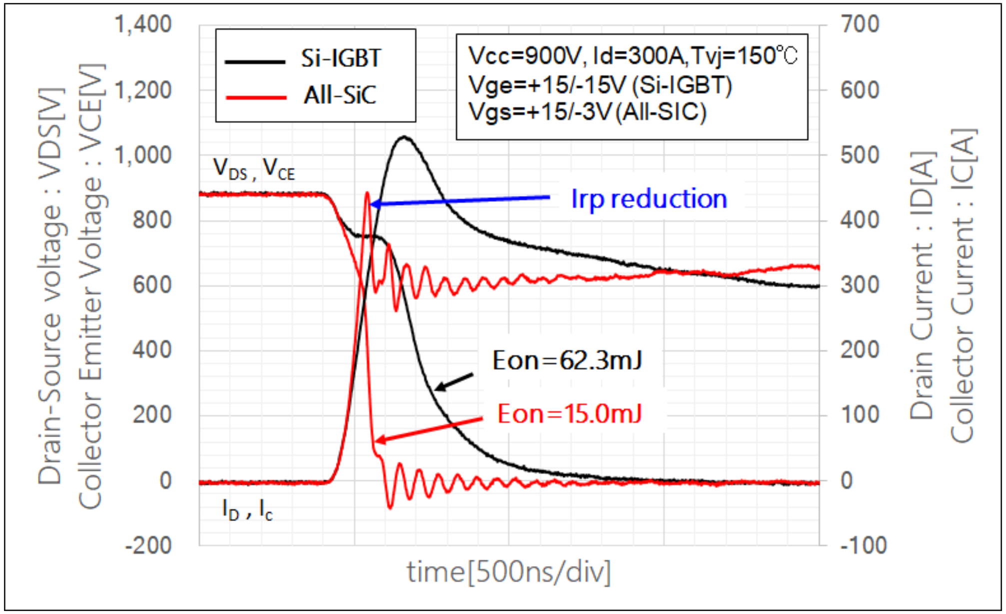
[conditions] V_{cc}=900V, I_D=300A, Tvj=150℃

Vge=+15/-15V (Si-IGBT), Vgs=+15/-3V (All-SiC)

Turn-off waveforms



Turn-on waveforms



The tail current of all-SiC module was reduced and the rising voltage was also faster compared to 7th generation Si IGBT module.

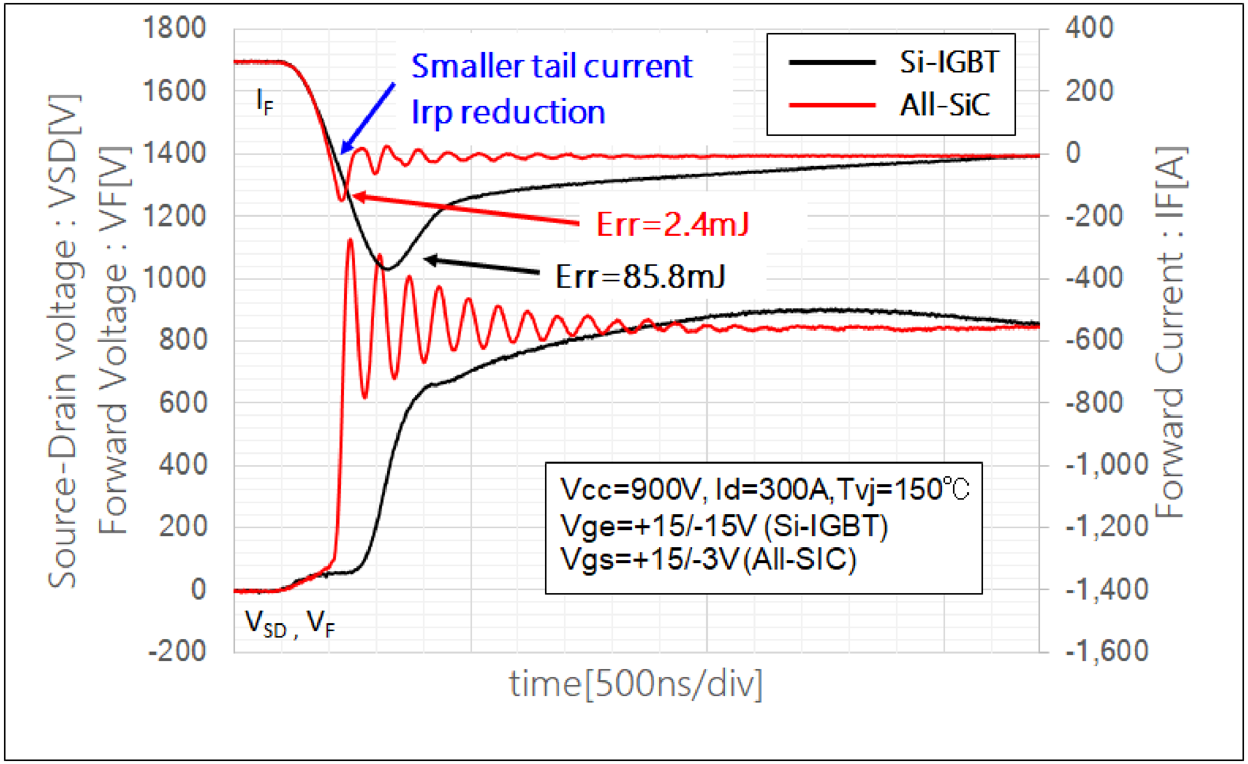
→ Eoff was reduced by 62%.

The peak current at turn on of the all-SiC module was reduced compared to 7th generation Si IGBT module.

→ Eon was reduced by 76%.

Reverse recovery of 1700V/300A All-SiC Module

[conditions] V_{cc}=900V, I_D=300A, Tvj=150℃



The tail current of all-SiC module was reduced compared to the 7th generation Si IGBT module.

→ Err was reduced by 97%.

Comparison of switching losses of 1700V/300A All-SiC Module

[conditions] V_{cc}=900V, I_D=300A, Tvj=150deg.C

Vge=±15V for Si-IGBT, Vgs=+15/-3V for All SiC

	Eon [mJ/pulse]	Eoff [mJ/pulse]	Err [mJ/pulse]	Esw_total [mJ/pulse]
All-SiC (2G)	15.0	37.1	2.4	54.5
7G-IGBT	62.3	98.2	85.8	246.3
Reduction Rate	76%	62%	97%	78%

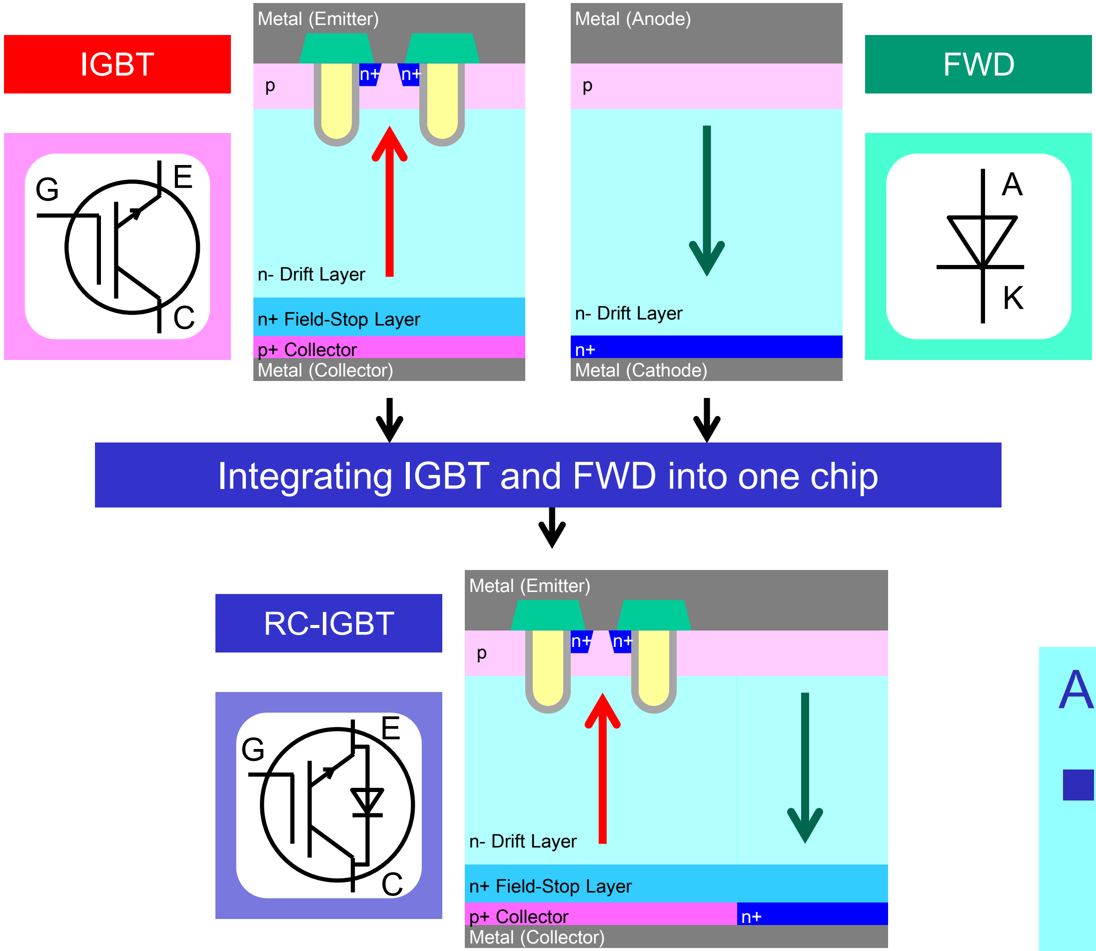
Total switching loss (Esw_total) was dramatically reduced by 78% compared to 7th generation Si module.

→Reduction of switching loss for the inverter is expected.

□ RC-IGBT for Wind Turbine

RC-IGBT Technology

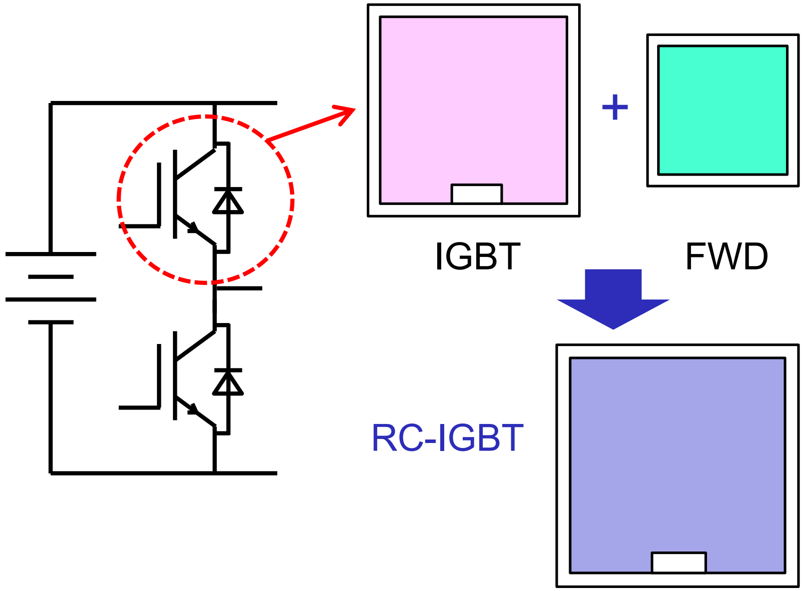
RC-IGBT Chip Structure



Basic Structure of RC-IGBT

- Based on the X Series IGBT/FWD technology

RC-IGBT Chip and Circuit Diagram

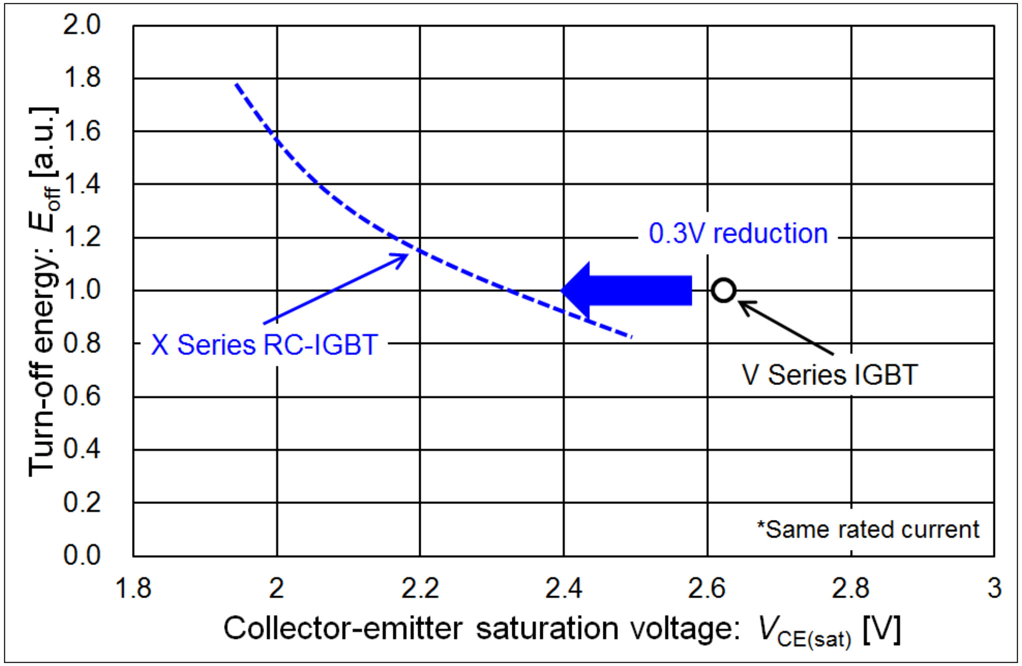


Advantage of RC-IGBT

- Total chip size reduction
  - Downsizing of the Module or High current rating with existing package
- Extending chip area
  - Chip Temperature reduction by Lower $R_{th(j-c)}$

RC-IGBT with X Series chip Technology (1700V device)

1,700V X Series RC-IGBT trade-off relationship between $V_{CE(sat)}$ and E_{off}



Measurement conditions:

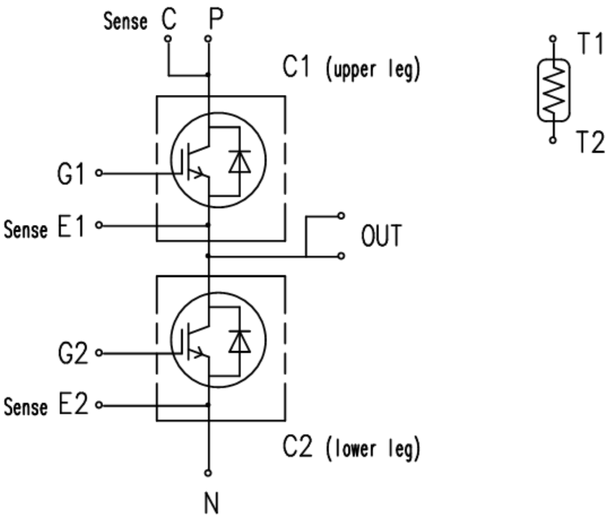
$V_{CE(sat)}$: T_{vj}=150°C, V_{GE}=+15V, I_C=rated current

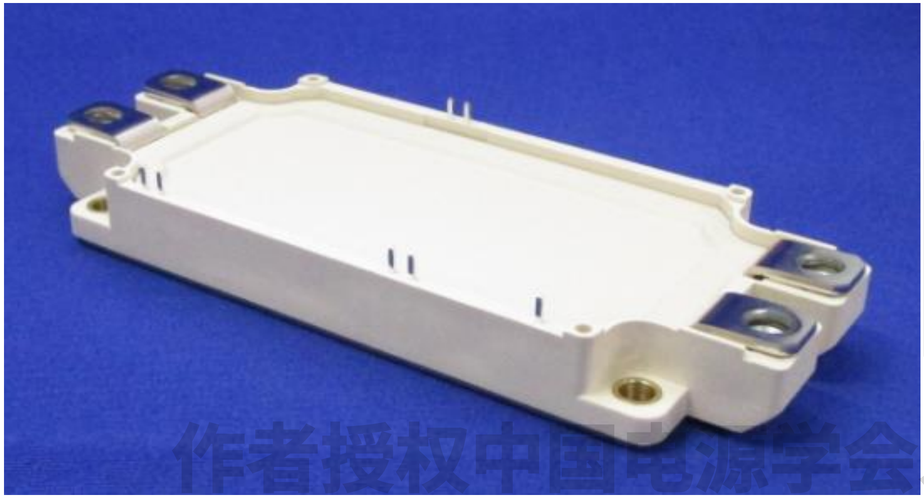
E_{off}: T_{vj}=150°C, V_{GE}=+15V/-15V, V_{CC}=900V, I_C=rated current

- 1,700 V X Series RC-IGBT trade-off relationship of IGBT was improved as compared with V Series IGBT.
  - $V_{CE(sat)}$ improvement by 0.3V under the same E_{off} condition

Dual XT 1700V/800A

Dual XT 1700V/800A	
Type Name	2MBI800XRNE170-50 (Solder pin type)
	2MBI800XRNF170-50 (Press-fit pin type)
Rated Voltage	1,700V
Rated Current	800A
Generation	7th-Generation “X Series”
Device	X Series RC-IGBT
Package	X Series M285 (Solder pin type)
	X Series M286 (Press-fit pin type)

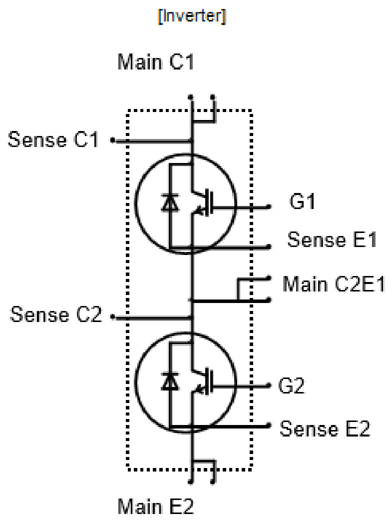


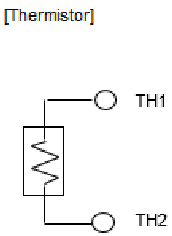


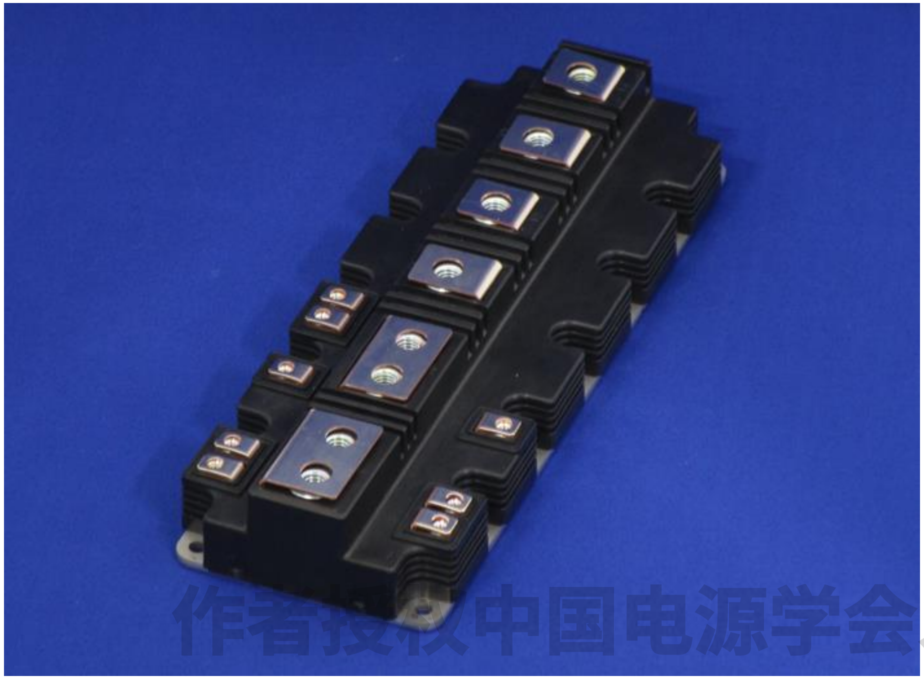
Rated Voltage	Rated Current [A]					
1,700V	225	300	450	550	600	800
DualXT	V Series IGBT + FWD					X-RC
	X Series IGBT + FWD					★

PrimePACK^{TM} 3+ 1700V/2200A

PrimePACK^{TM} 3+ 1700V/2200A	
Type Name	2MBI2200XRXF170-50
Rated Voltage	1,700V
Rated Current	2.200A
Generation	7th-Generation “X Series”
Device	X Series RC-IGBT
Package	X Series M291





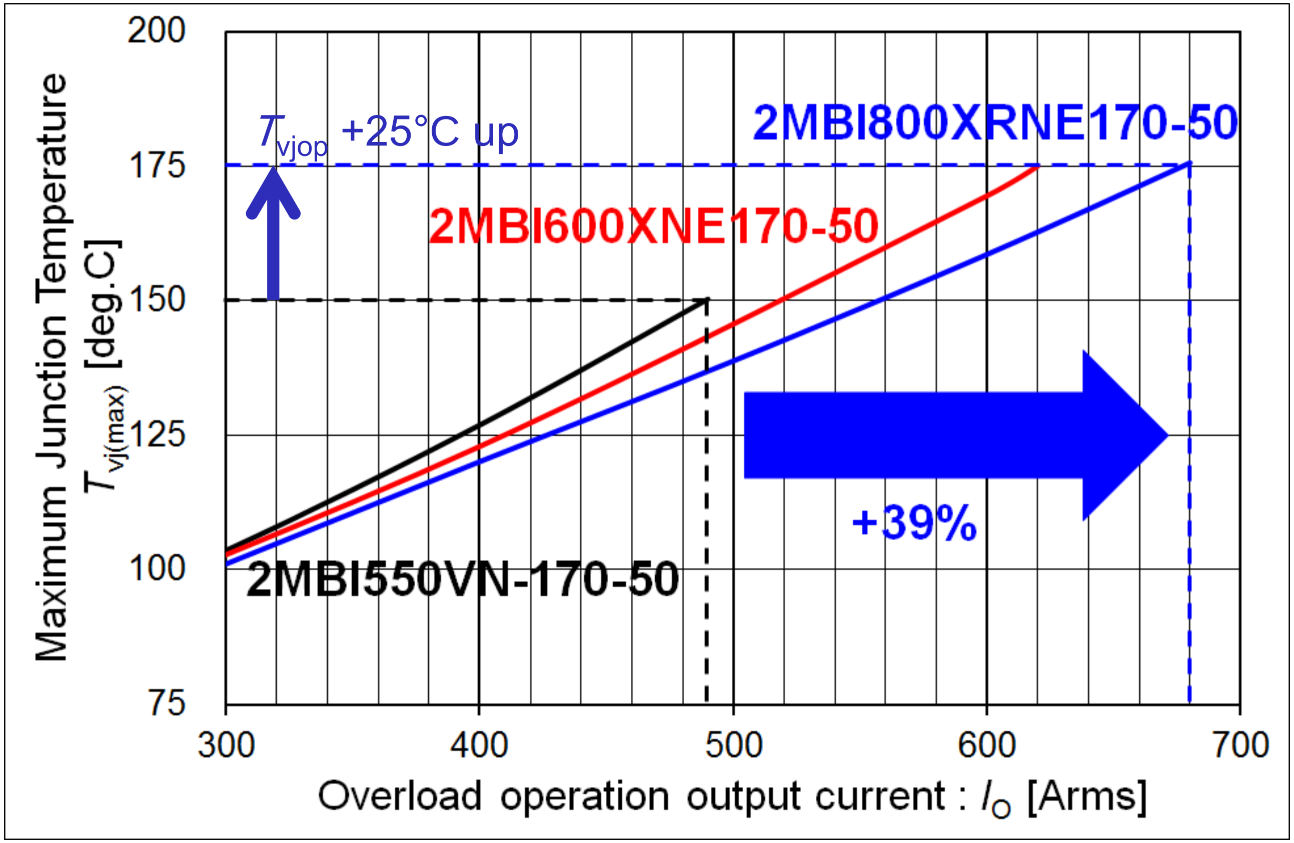


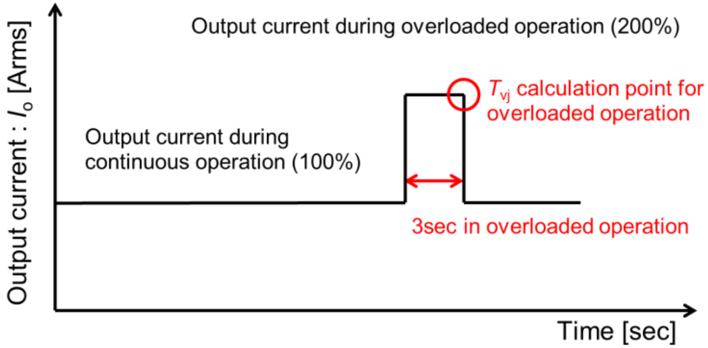
Rated Voltage	Rated Current [A]			
1,700V	1,000	1,400	1,800	2,200
PrimePACK^{TM}	V Series IGBT + FWD			X-RC
	X Series IGBT + FWD			★

Note:

PrimePACK^{TM} is registered trademark of Infineon Technologies AG, Germany

Calculation results for relationship between T_{vj} and I_o
(under the overload operation condition)





Calculation conditions:
T_{vj}=150deg.C, V_{CC}=900V, fo=50Hz, f_c=2kHz, Power factor=0.9, Modulation rate=1.0, Ambient temperature T_a=50°C, same cooling conditions

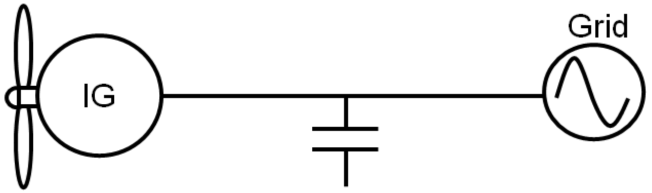
- 1,700V X Series RC-IGBT module Dual XT has been able to expand the I_o by 39% with same package size during overload operation compared with V Series.
  - Reducing the power dissipation and $R_{th(j-c)}$
  - Expanding the T_{vjop} from 150deg.C to 175deg.C

Wind power generation systems

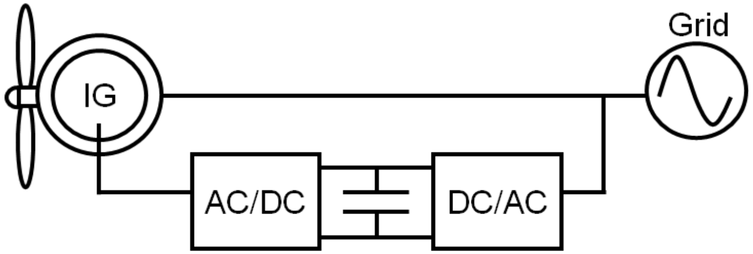
What is one of major application for 1,700 V IGBT modules?

- Wind power generation systems

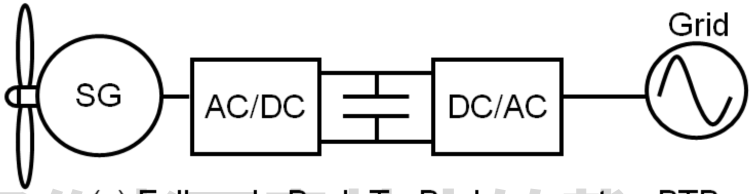
DFIG and BTB systems utilize power conversions.



(a) Induction Generator: IG



(b) Doubly-Fed Induction Generator: DFIG



(c) Full-scale Back-To-Back converter: BTB

- DFIG

Power converter is connected to the rotor to control the rotor frequency and current.
The converter size is around 30% of the system.

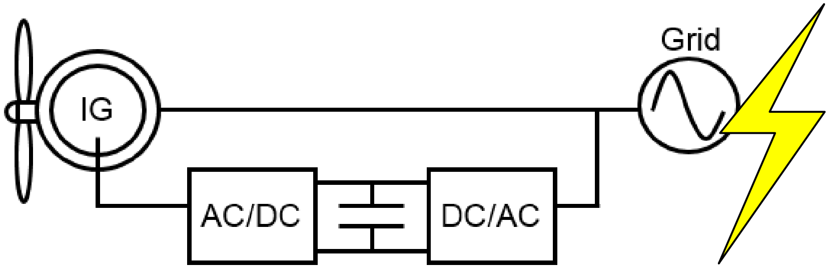
- BTB

Power converter controls full power and full speed range of the system.

Low Voltage Ride Through (LVRT) function

Fuji Electric
Innovating Energy Technology

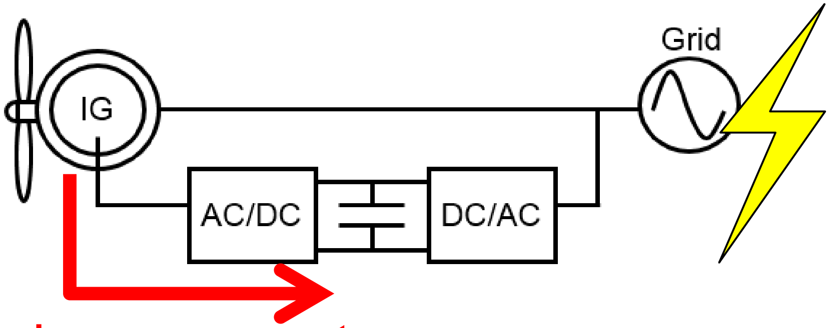
Instantaneous voltage drop



Instantaneous voltage drop occurs in the grid…

- The system will stop.
- There is the risk of instability to the grid.

LVRT operation



Large current

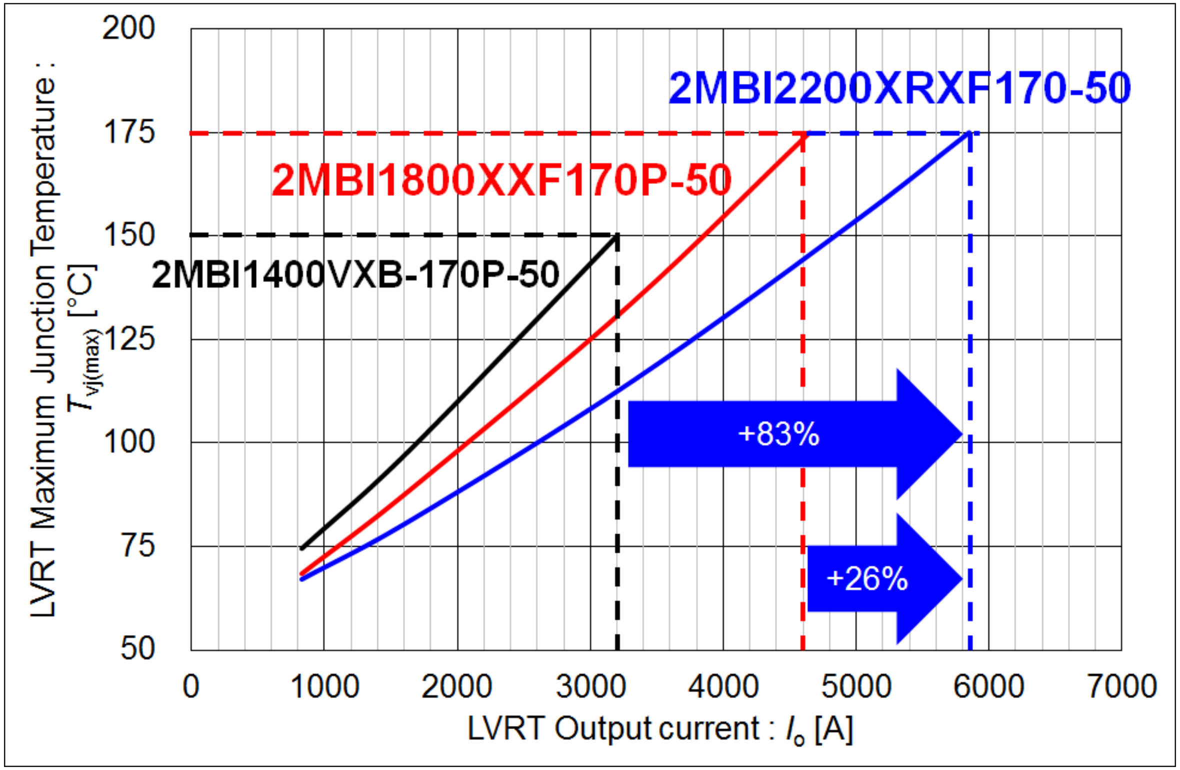
In case of the LVRT operation…

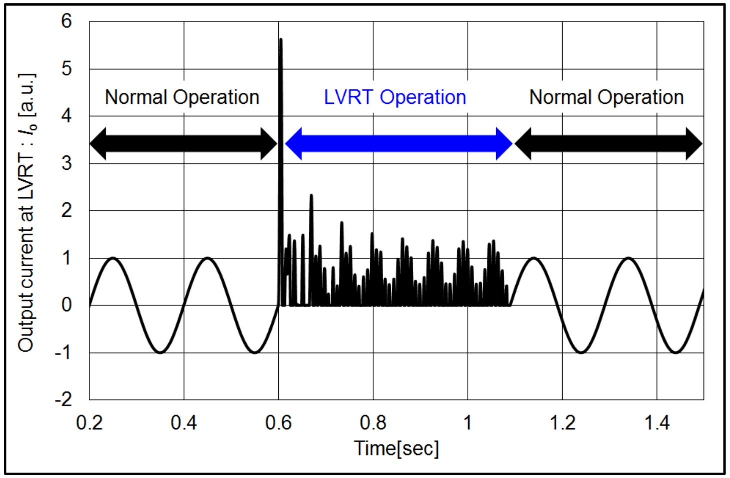
- Large current will flow from generator to the capacitor through the FWD of rotor side.

- The operation continuous function (LVRT) becomes important to supply the stable power to the grid.

- Large current capability of FWD is important.

Calculation results for relationship between T_{vj} and I_o
(under the LVRT operation condition)





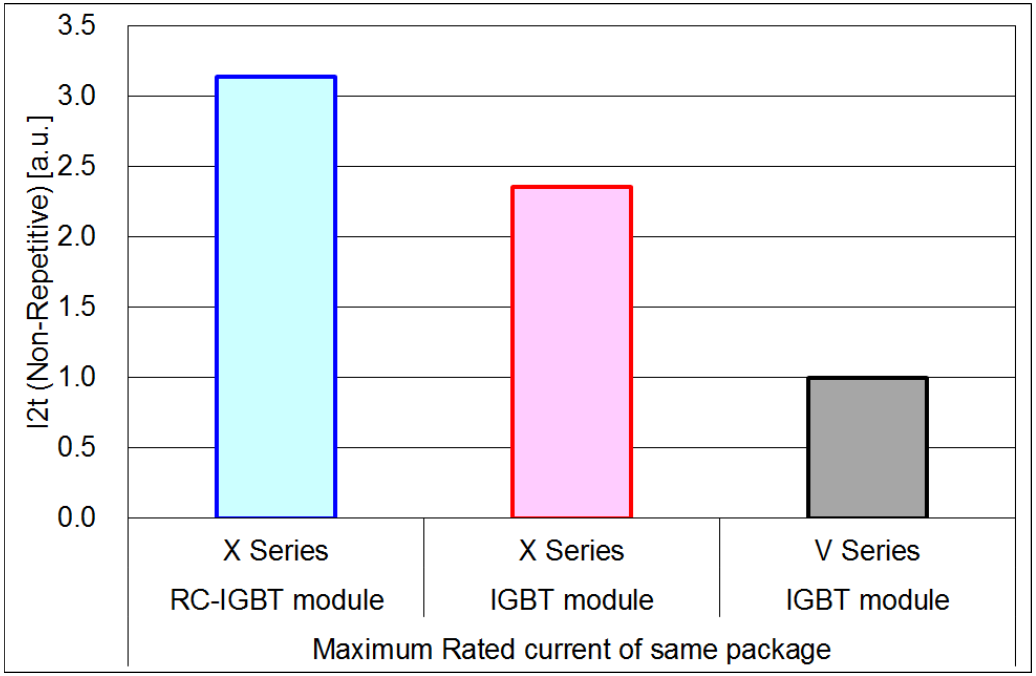
Calculation conditions:
T_{vj}=150deg.C, V_{CC}=1100V, fo=1.5Hz, f_c=2.5kHz, Power factor=-0.65, Modulation rate=0.15, Ambient temperature T_a=50°C, same cooling conditions

- 1,700V X Series RC-IGBT module PrimePACK^{TM} has been able to expand the I_o by 83% with same package size during overload operation compared with V Series.
  - In X Series RC-IGBT, IGBT and FWD regions are optimized.
  - The temperature balance inside the device is optimized.
  - Therefore, the thermal resistance and large current capability are improved.

Note:PrimePACK^{TM} is registered trademark of Infineon Technologies AG, Germany

I^2t capability (Surge current capability)

Fuji Electric
Innovating Energy Technology



Measurement conditions:
T_{vj}=150deg.C, t=10ms (Half sine wave form), Non-Repetitive

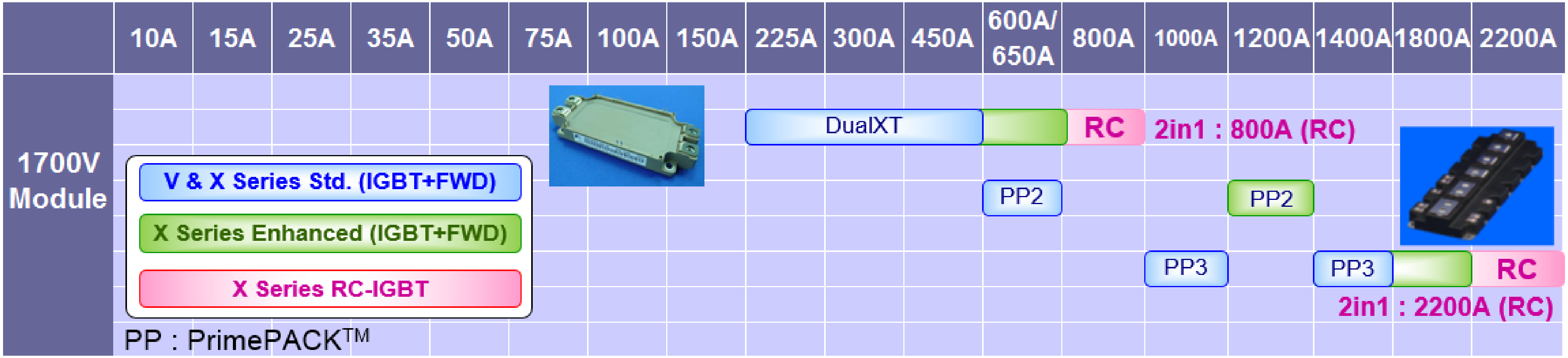
- 1,700 V X Series RC-IGBT module has increased over 200% I^2t capability compared with conventional V Series.
  - IGBT region becomes buffer layer of heat during the FWD operation, which is the reason of high I^2t capability.

Product Line-up of 1,700 V X Series RC-IGBT Modules

Fuji Electric
Innovating Energy Technology

- X Series RC-IGBT Modules can achieve more enhancement & downsizing.
- X Series IGBT Module family will be expanded for premium range by X Series RC-IGBT.

1700V 7th-Generation "X Series" RC-IGBT Modules for Industrial Application



PP : PrimePACK™

Note: PrimePACK™ is Trademark or registered trademark of Infineon Technologies AG, Germany