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Changes for the Better

CPSS ISESC 2024

功率芯片和功率模块技术的进步

Advancements of Power chip and Module technology

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M-00341

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01 Market Growth of Power Semiconductors

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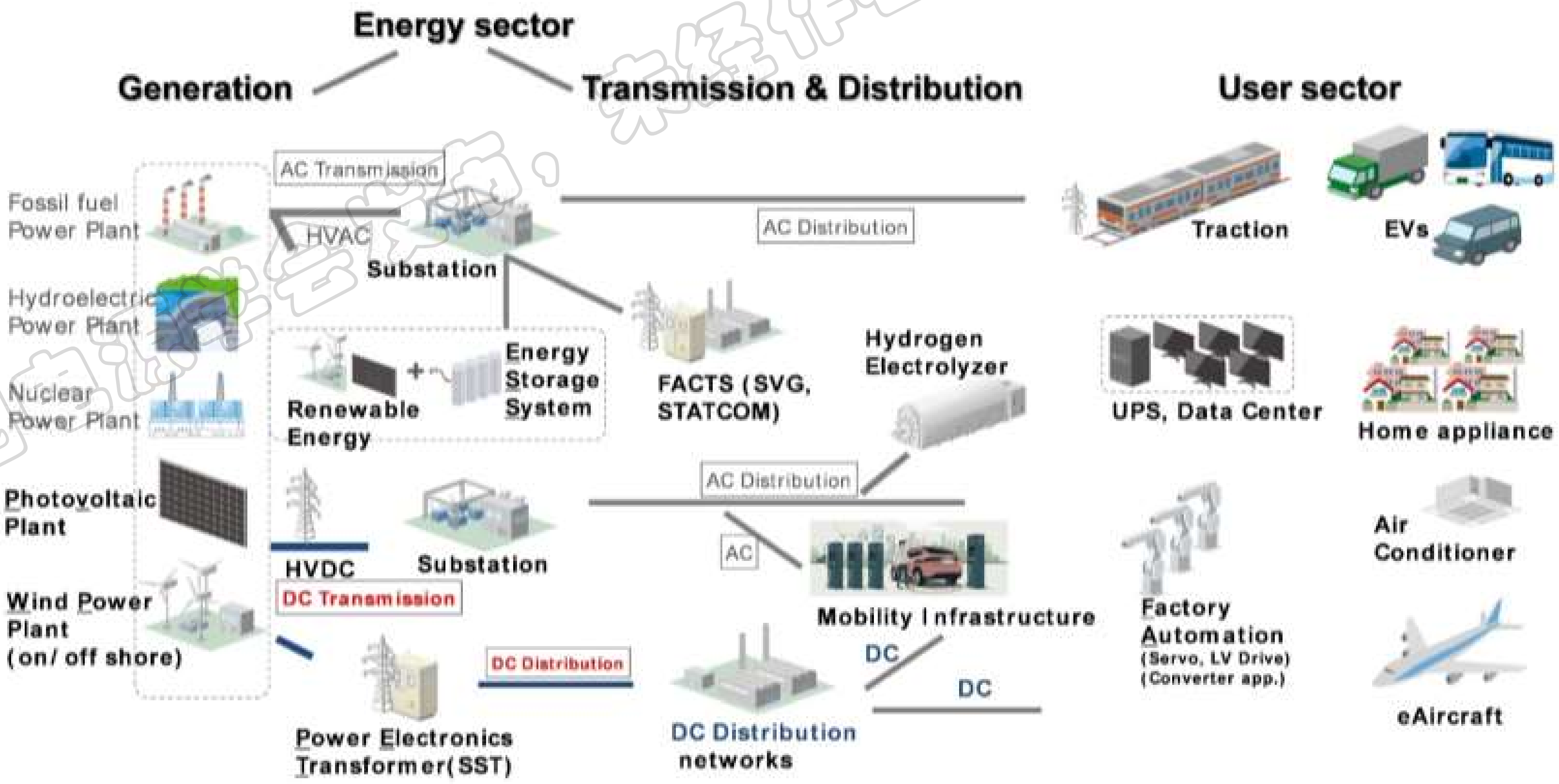
The power semiconductor market driven by the energy-wise applications, is projected to grow at a CAGR of approximately 10%, and is divided into two main sectors as shown below.

https://www.iec.ch/basecamp/power-semiconductors-energy-wise-society

Power semiconductors for an energy-wise society
Published Oct. 2023



Power Semiconductor Growth driven by energy-wise society

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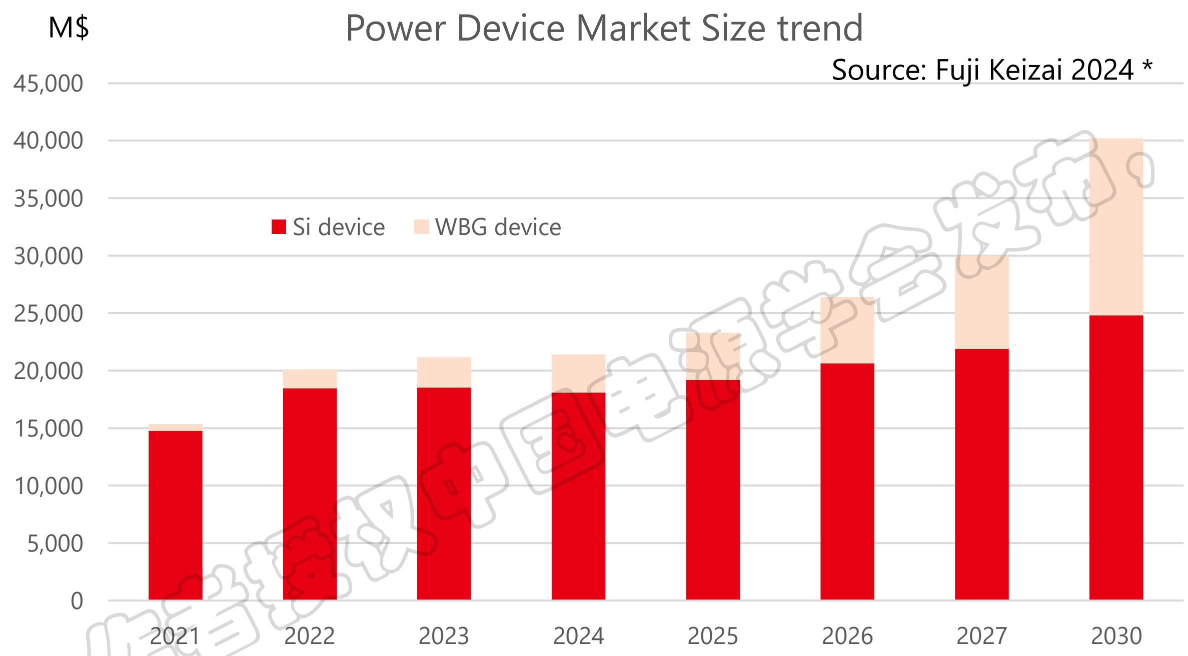
There are two major power semiconductor materials: Silicon and WBG.
While WBG is experiencing rapid growth in the EV market, the silicon IGBT market, which has been established since the 1990s, continues to grow and dominate the majority.

The development of high-performance IGBT remains crucial, as well as SiC.



WBG Growth

IGBT Growth

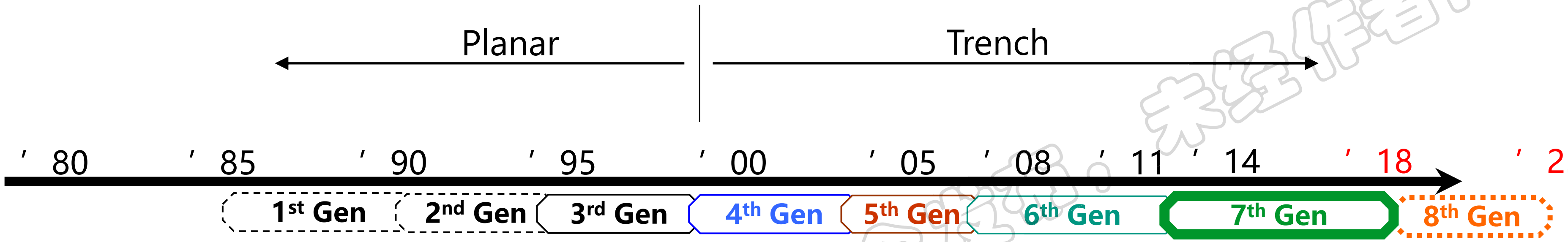
Both Si and SiC are the key components for the energy-wise applications

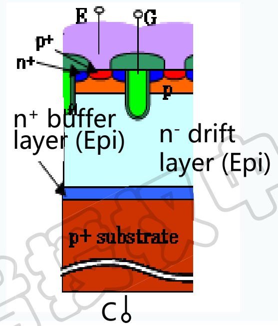
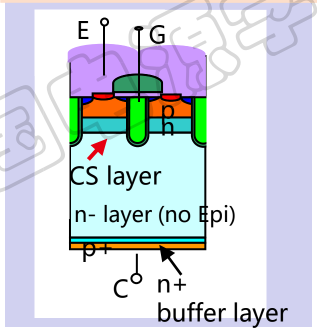
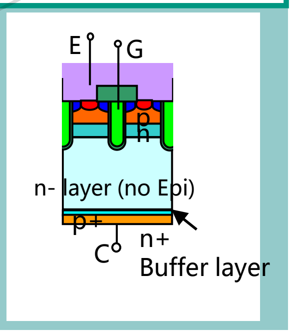
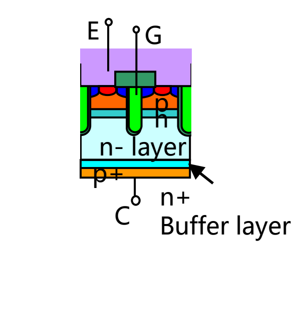
*: FUJI KEIZAI CO., LTD. 「2024 Current status and future outlook of markets for power devices and power electronics-related equipment」

02 Progress of IGBT technology

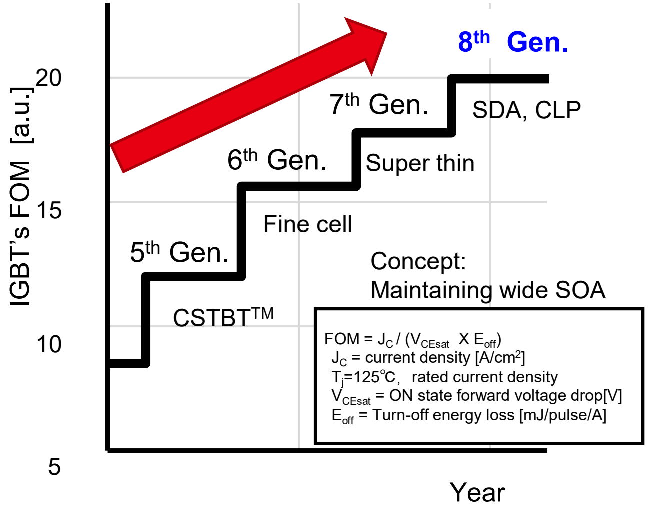
Progress of IGBT chips to date

Early IGBTs utilized planar technology. Since the 4th generation, trench technology has been employed. The carrier storage layer has been introduced from the 5th generation to reduce on-state voltages. The 6th and 7th generations use thinner wafter and improved buffer layers. With every generation, technology evolves to achieve higher performance.

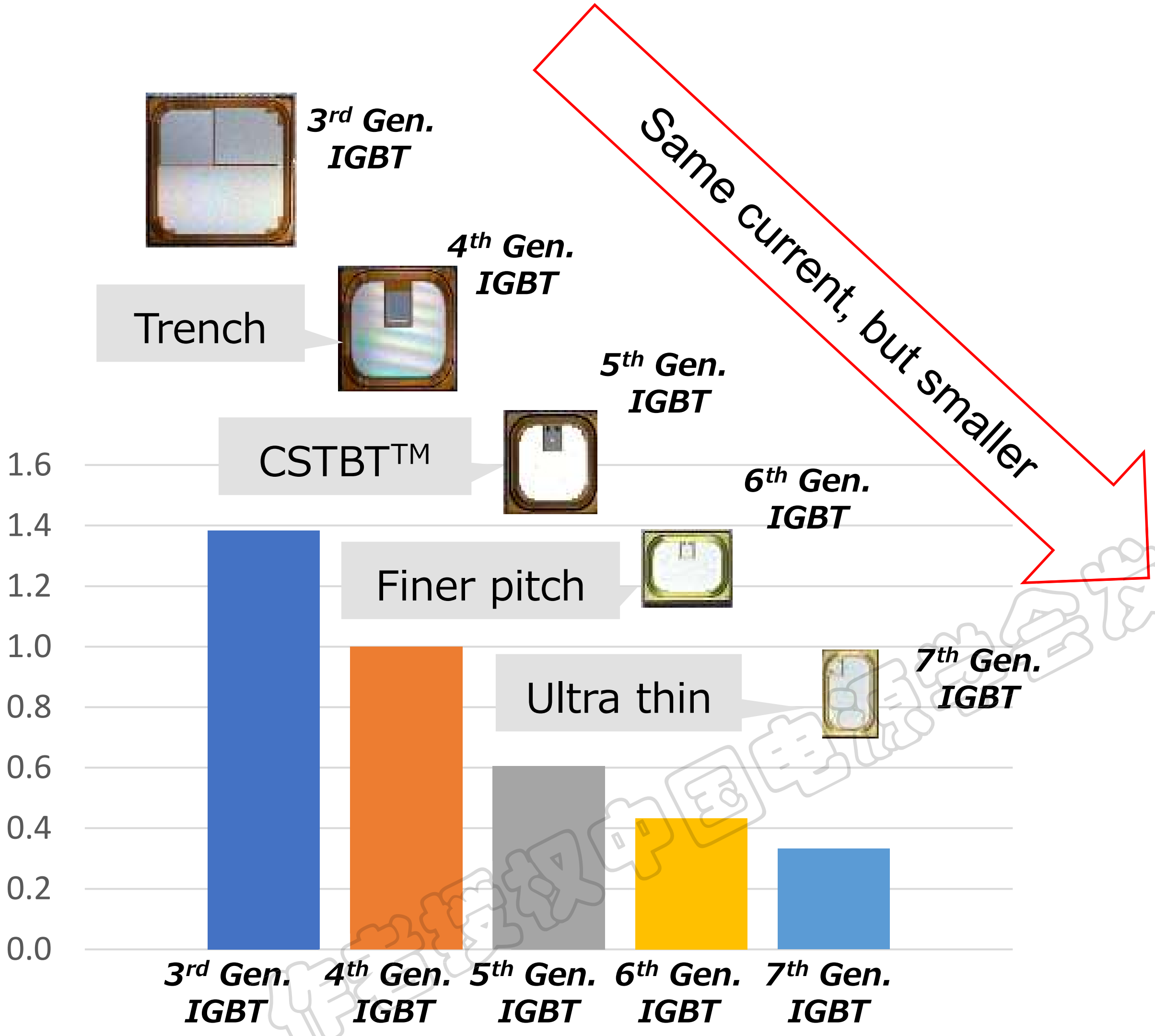


	第4代 IGBT	第5代 IGBT	第6代 IGBT	第7代 IGBT
IGBT结构 (1200V)				
核心技术	细薄工艺 沟槽栅型元胞	CSTBT™ 结构 薄背面(PT-->LPT)	薄晶圆 Design rule refining	超薄晶圆 超细工艺
损耗降低 (与第4代相比)	100%	减少35%	减少50%	减少65%

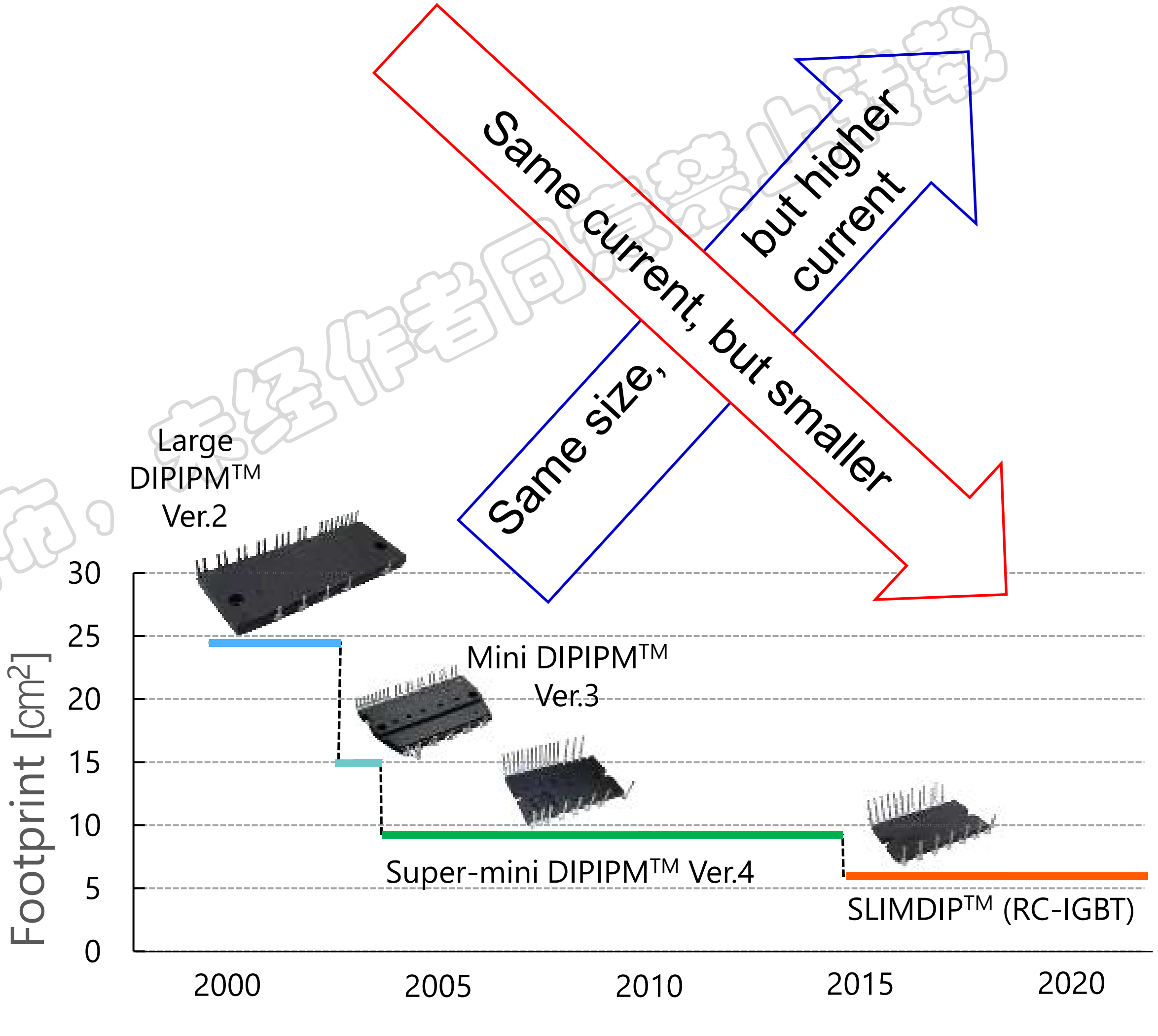
FOM improvement
(normalized by 1st gen. as 1)



Progress of IGBT chips to date

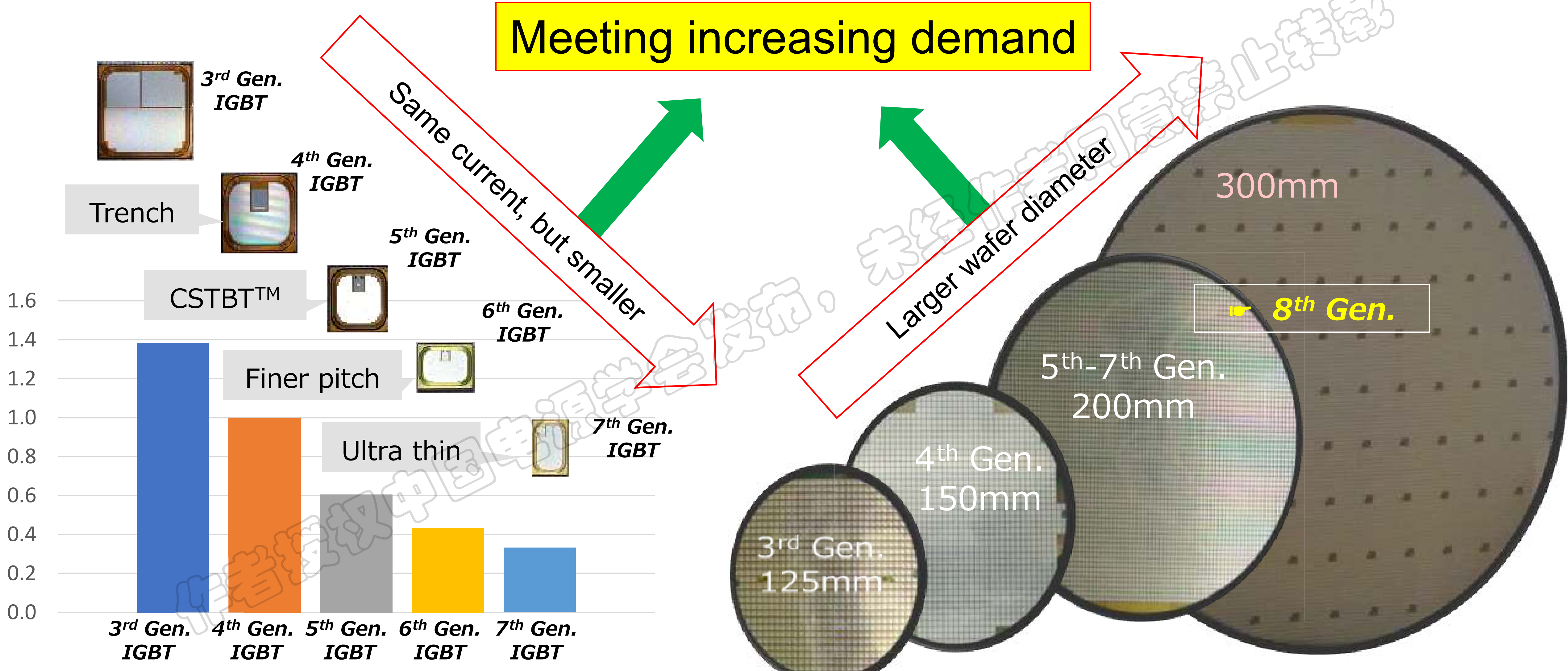


Chip size evolution (600V/10A)



15A/600V package size reduction

Progress of IGBT chips to date

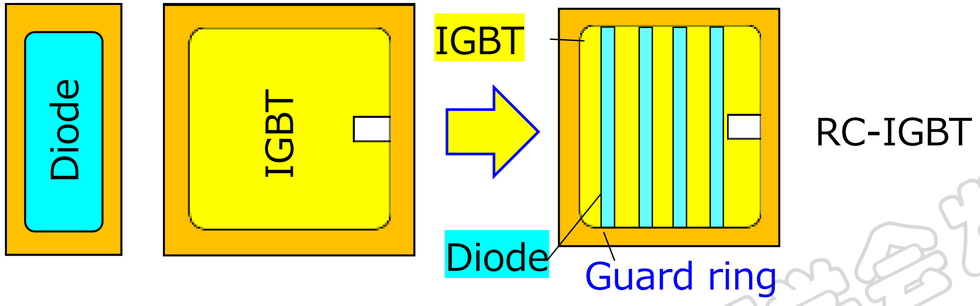


Chip size evolution (600V/10A)

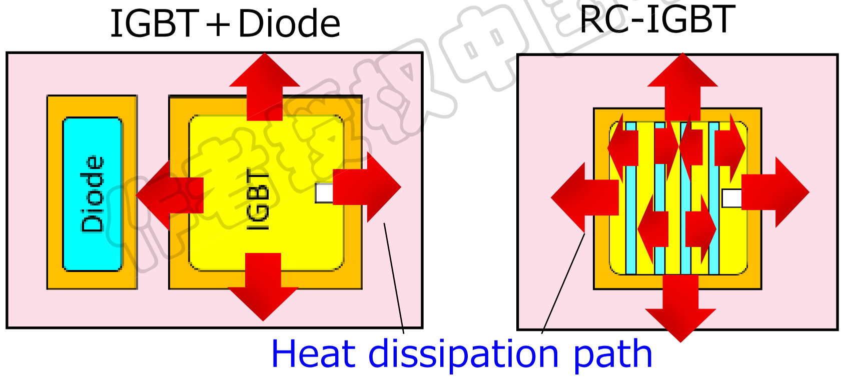
RC-IGBT, a combined device

By integration of IGBT and Diode on a single die, ①better power density, ②better heat spreading capability hence longer lifetime, and ③downsizing of the module can be achieved. RC-IGBT has a good similarity with SiC-MOSFET, where body diode can be used.

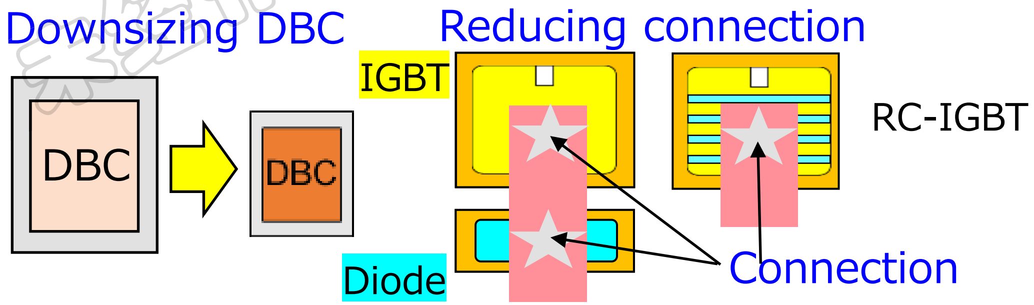
①Integration of IGBT and Diode
☞Chip downsizing by sharing a guard ring
☞Similarity with SiC MOSFET



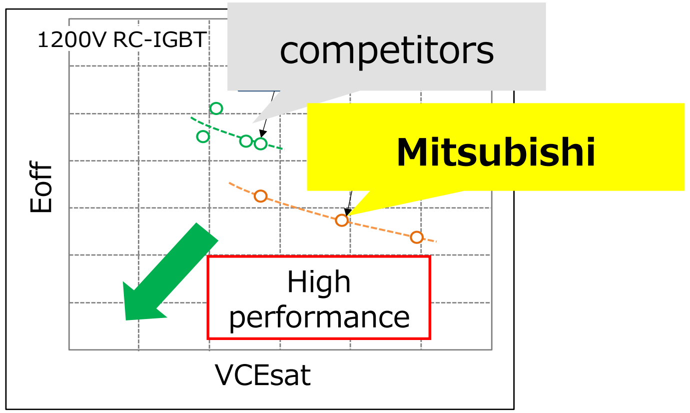
②Increased heat dissipation path and area
☞Reduced thermal resistance and temp. ripple



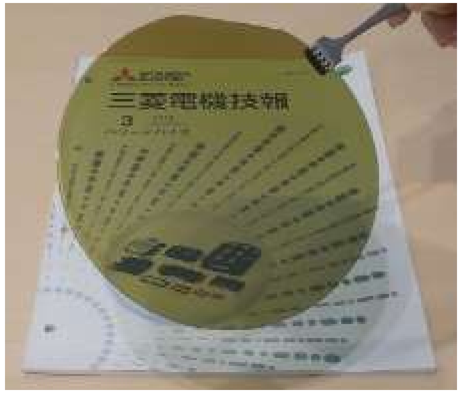
③Shorten the interval between IGBT/Diode
☞Material reduction/Number of chip reduction
☞Reduction of chip-to-chip connection



■ Automotive RC-IGBT benchmark

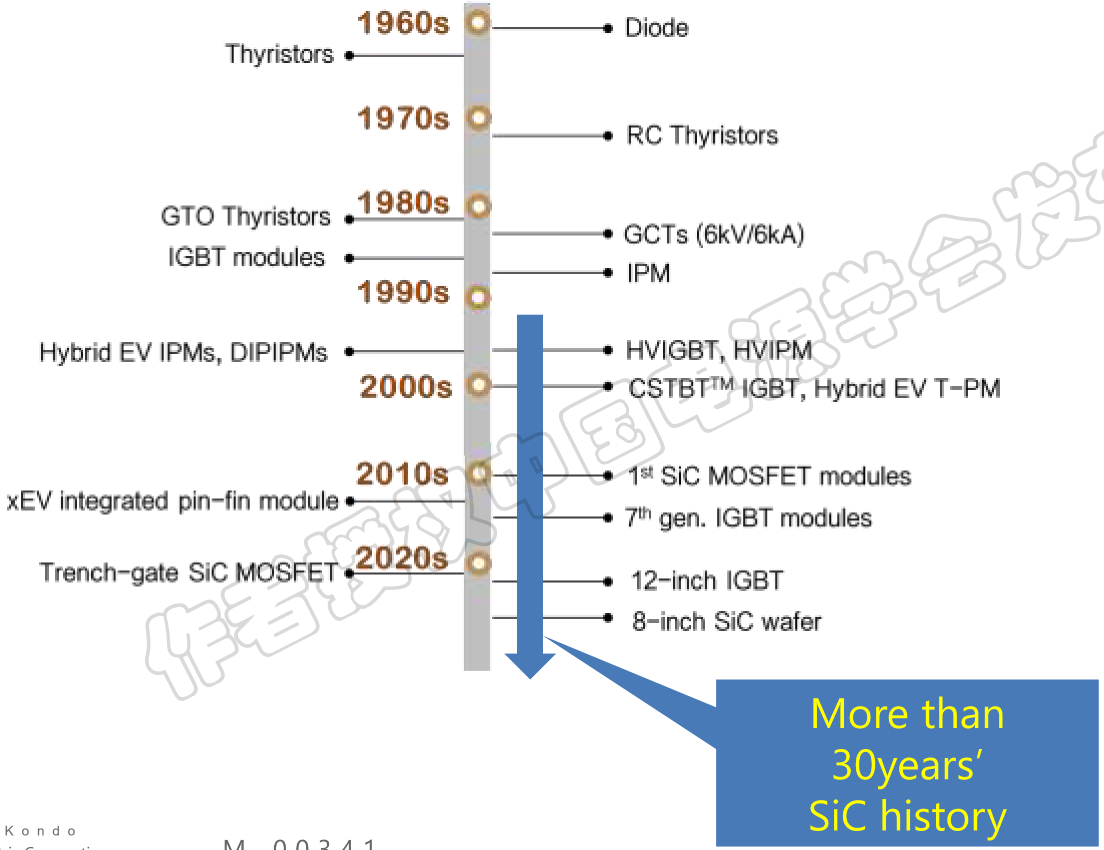


03 Progress of SiC technology



Brief History of Mitsubishi Si and SiC Device

Mitsubishi Electric has been actively engaged in the development of new power devices. It started from Silicon devices, including Diodes, Thyristors and IGBTs. When IGBT was still in the cradle, namely, 1990's, we started the development of SiC power device.



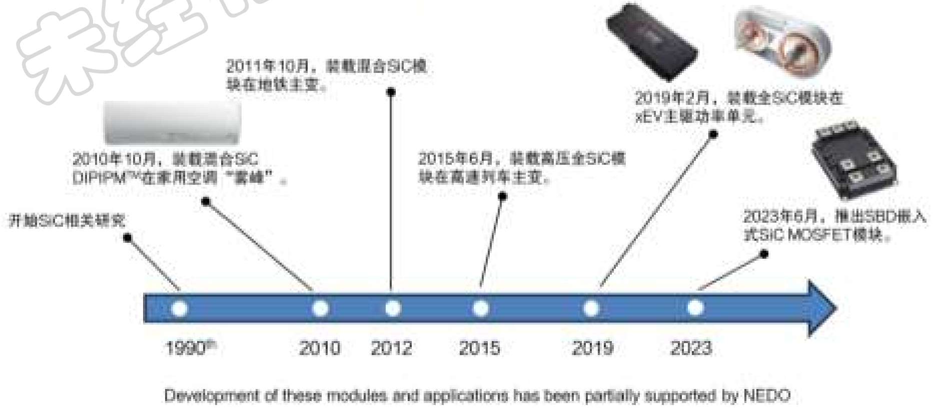
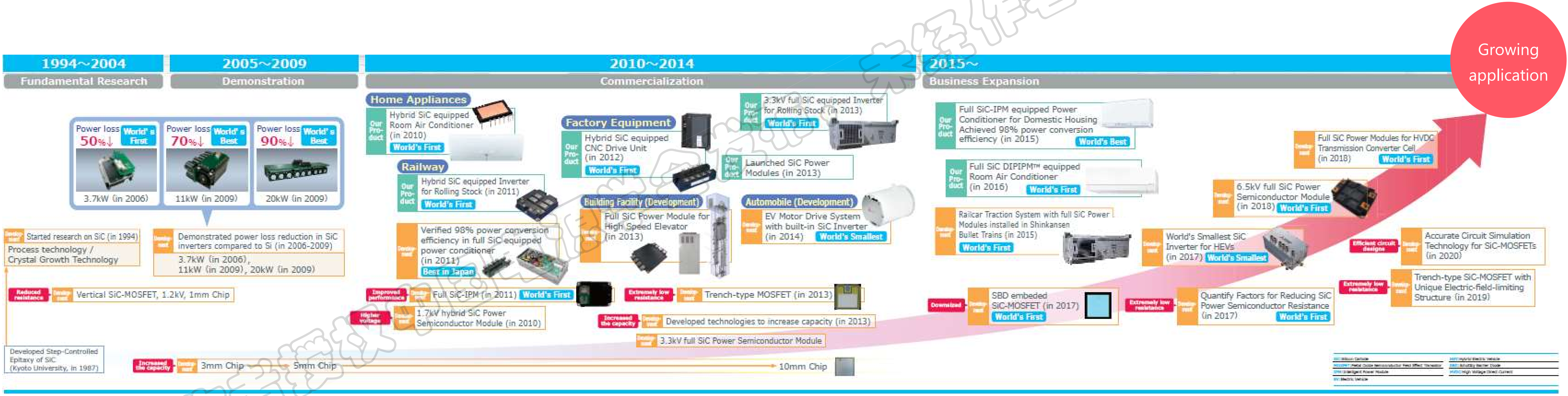


图2：三菱电机SiC模块发展路线图

Research history of Mitsubishi SiC devices from 1990's

Mitsubishi Electric has power electronics business as well as power device. Taking advantage of this, we took the lead in utilizing SiC device by internal intimate collaboration.

Example is a traction converter, where we could reduce motor losses and enhance regenerative power by using SiC. Such a finding was very important in the early stages.



Development of these modules and applications has been partially supported by Japan's Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology development Organization (NEDO).

Mitsubishi SiC MOSFET development roadmap

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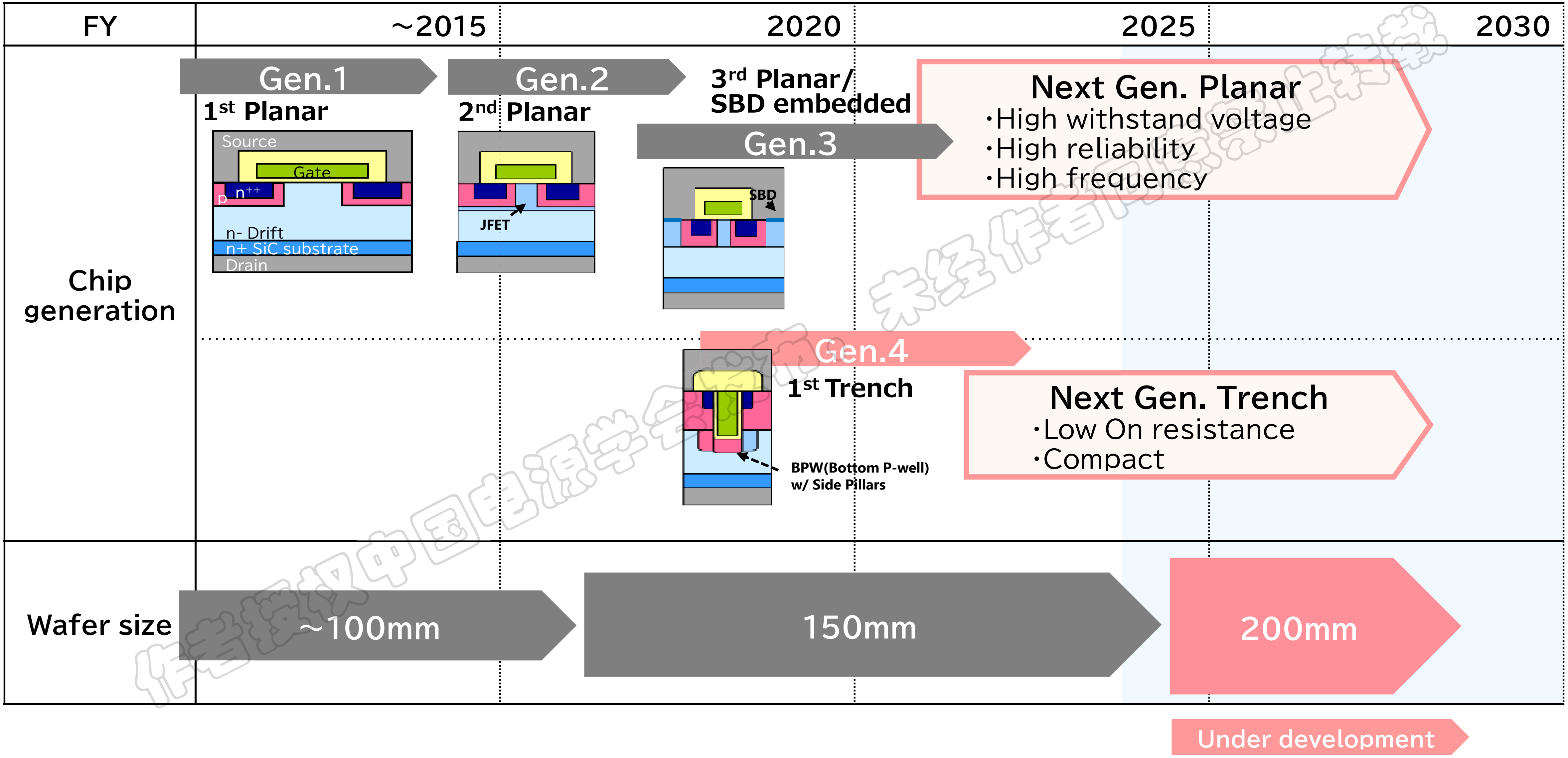
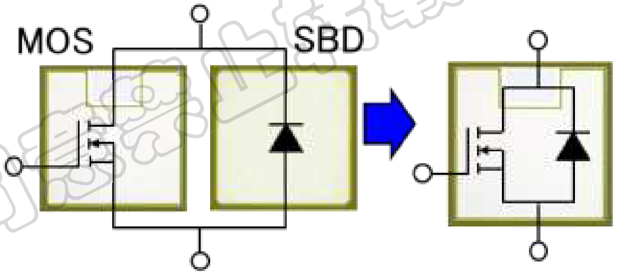


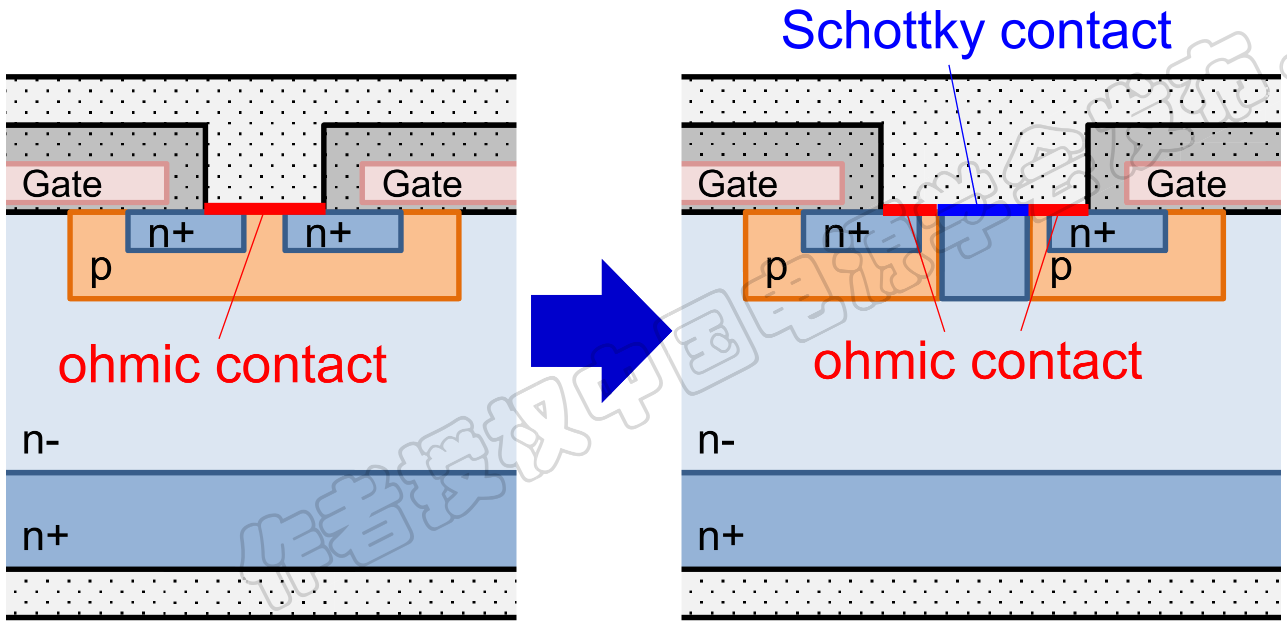
3rd Gen. SBD-embedded MOSFET

✓ No bipolar current flowing in reverse direction, hence free from Body Diode degradation

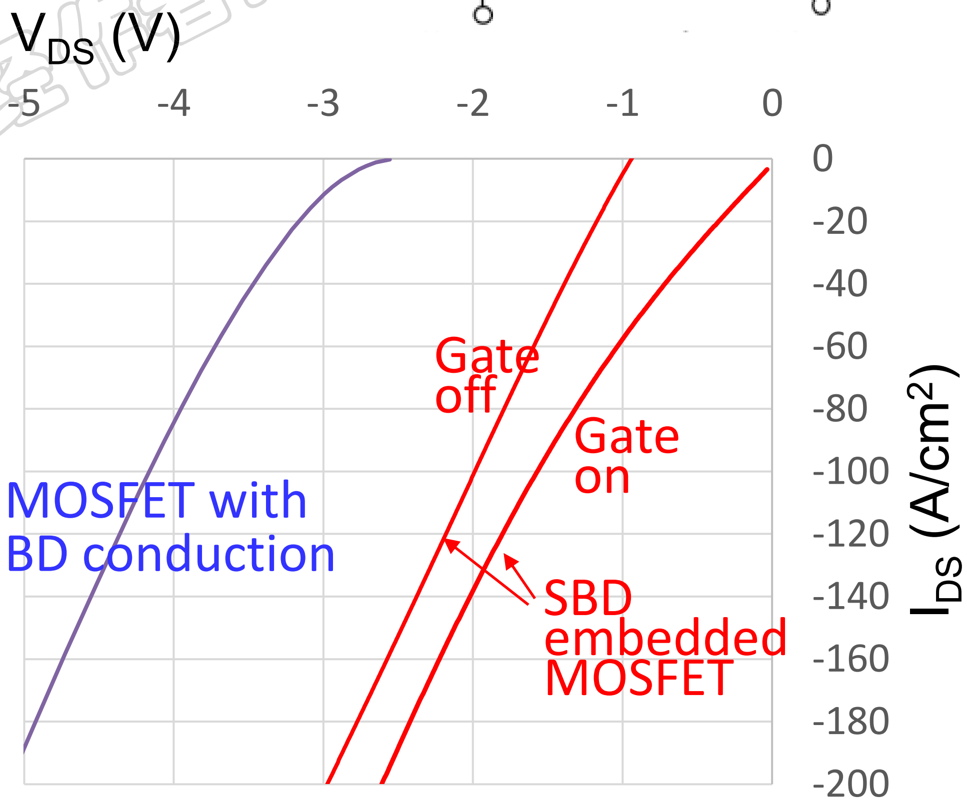
✓ No anti-parallel SBD required, reducing total chip area

✓ Enough surge current capability is maintained





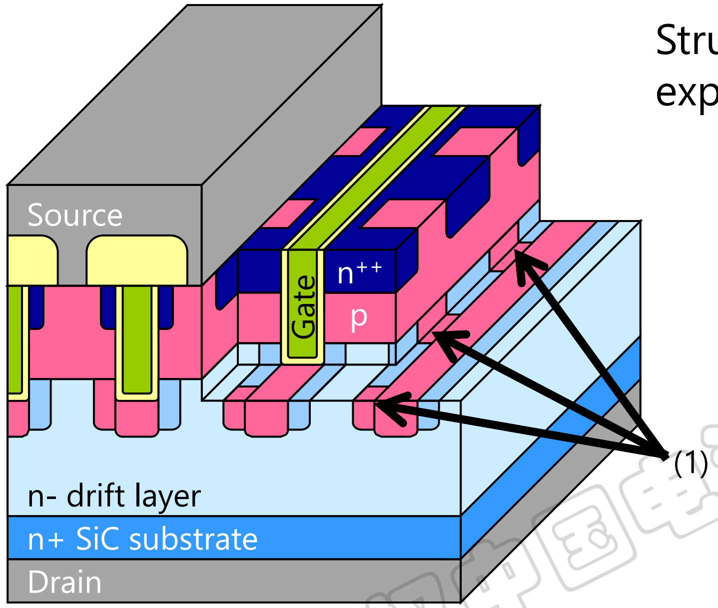
Cross sectional view of MOS cell



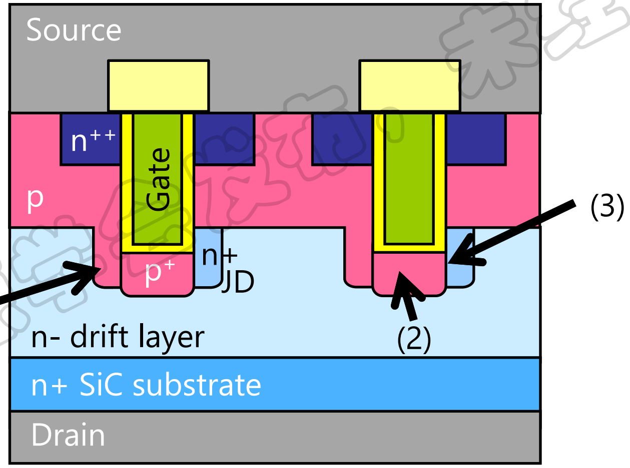
Reverse I_{DS}-V_{DS} characteristics

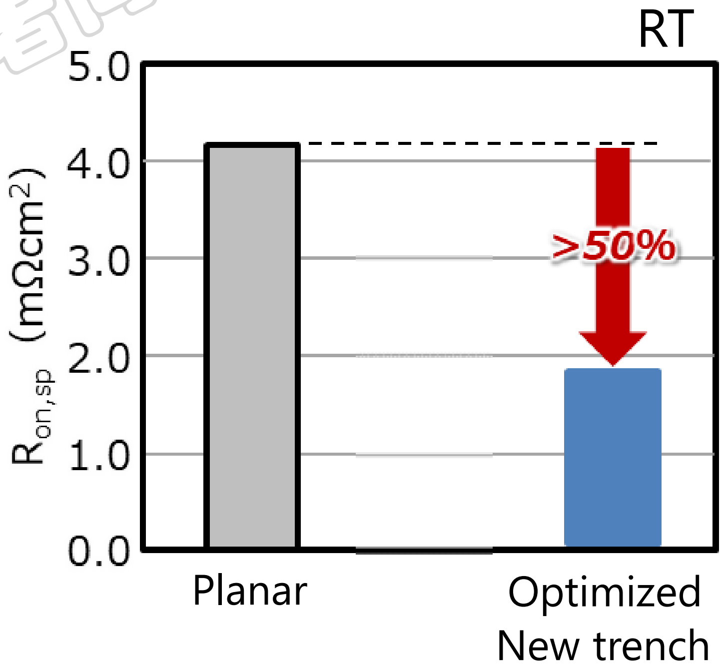
4^{th} Gen. Trench MOSFET

- ✓ Mitsubishi original structure(SPW, J-FET doping) realizes high gate reliability, low Ron, and low switching loss
- ✓ Trench type improves Ron performance by more than 50% versus planar type



Structure optimized with trench technology experience by Si product development





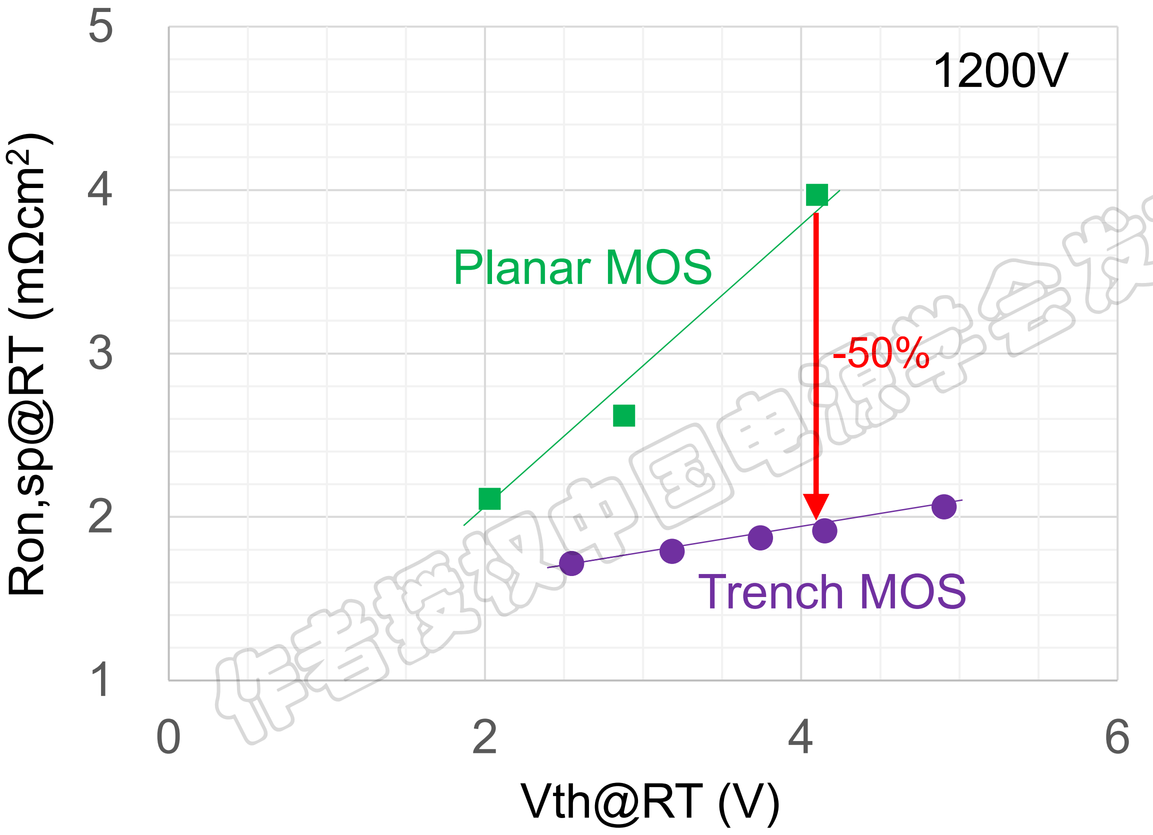
Features
(1) Trench bottom P-well structure
(2) Side p-well structure
(3) JFET doping technology

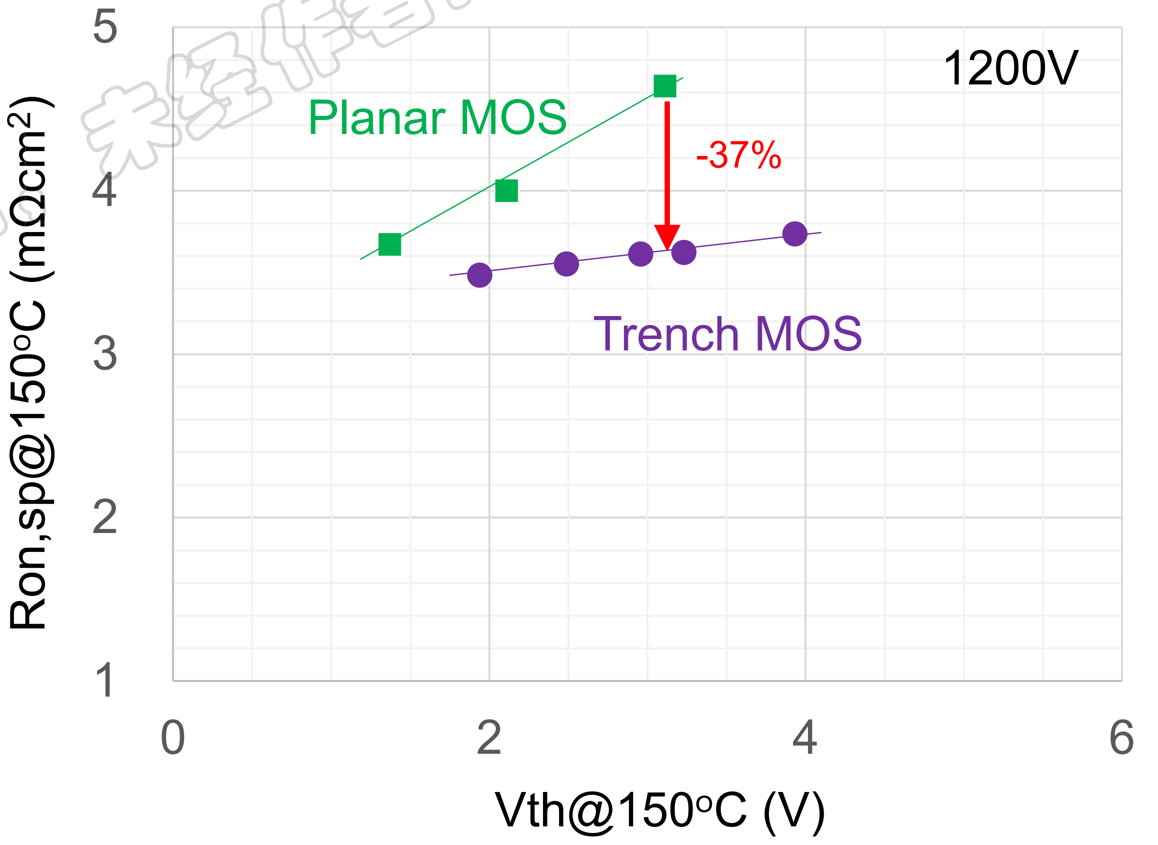
High reliable gate characteristics (-Relaxing high voltage strain in gate layer)
Low switching loss (-Releasing electricity stack cause of extra switching losses)
Low on-state resistance (-Adapting lower Ron current pass)

Y.Fukui et al., ICSCRM2019, Kyoto, 2019, Mo-1A-02. R.Tanaka et al., ICSCRM2019, Kyoto, 2019, Mo-1A-03.

Ron v.s. Vth improvement by Trench MOSFETs

- ✓ World-class low on-resistance trench MOSFETs have been realized.
- ✓ On-resistance is remarkably reduced especially in higher Vth range compared to our planar MOSFETs.





4^{th} Gen. Trench MOSFET Performance

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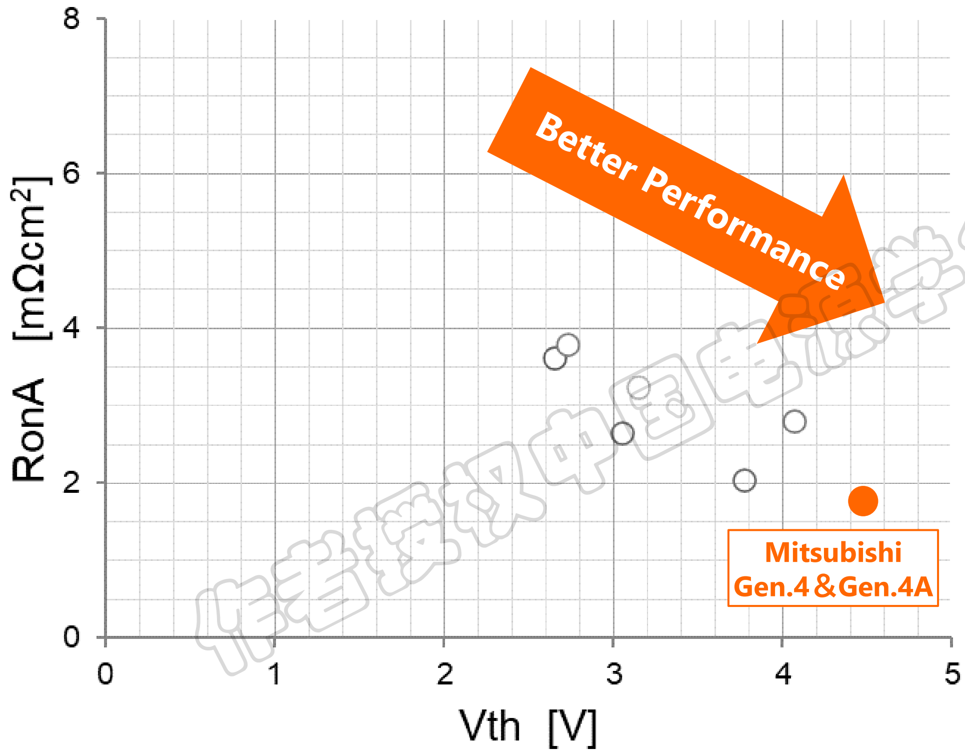
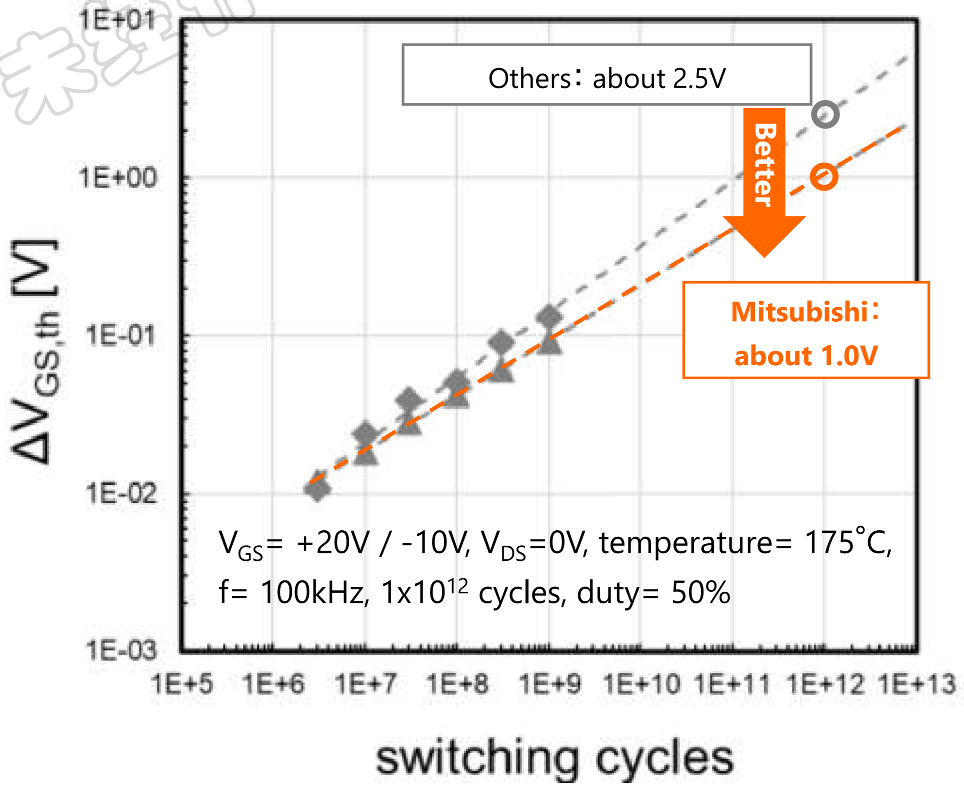
- ✓ Best-in-class Ron and high Vth
- ✓ High Vth minimizes false ON
- ✓ High quality gate oxide prevents Vth variation.
- ✓ Stable Ron performance in a long-term use

Ron vs Vth (25°C)



Vth variation over AC stress



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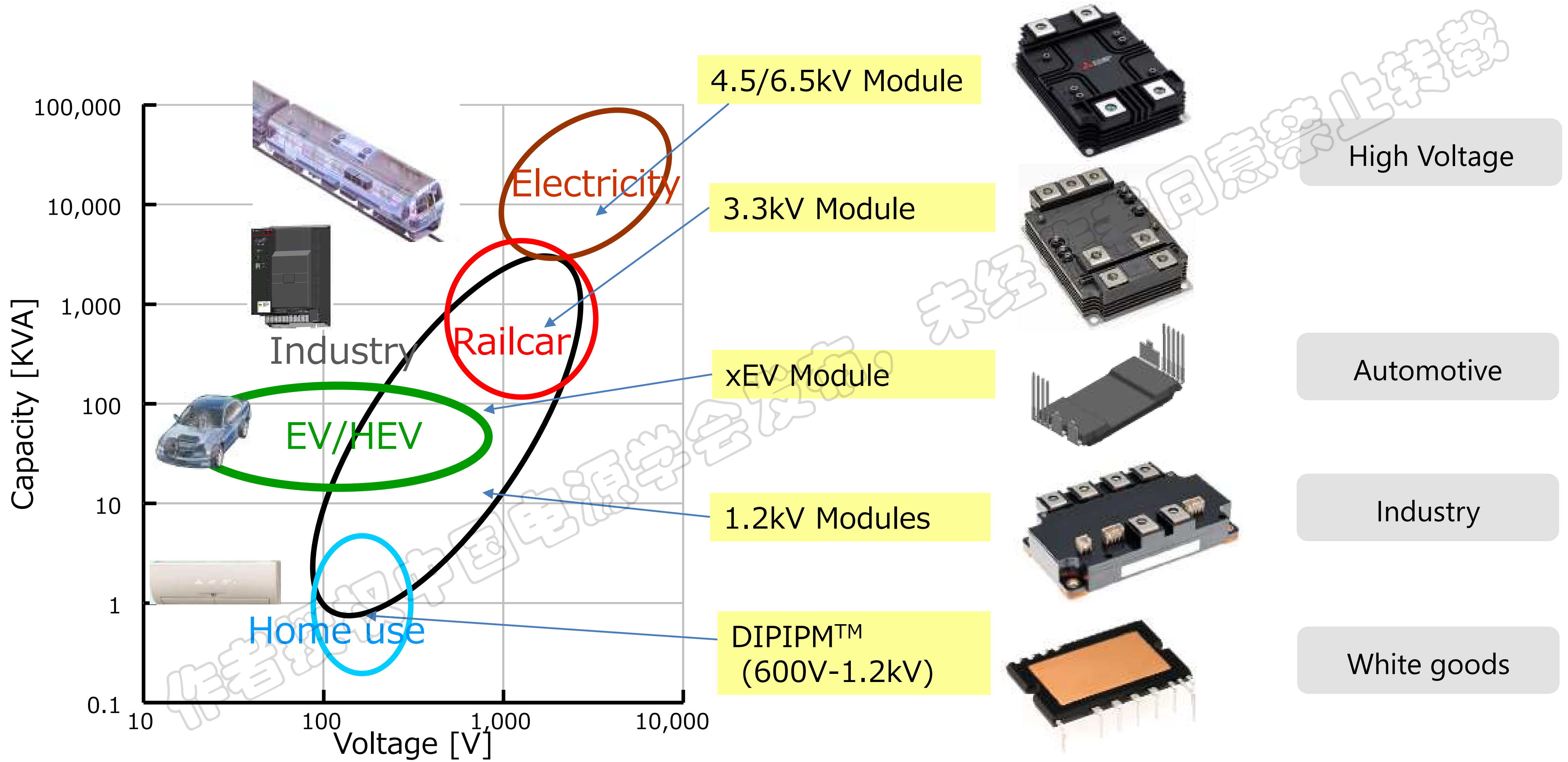
04 Power modules and IPMs for growing applications

4-1 Applications and Modules



Progress of HV IGBT and SiC modules

Higher current density has been realized by applying novel chip and packaging concepts.

3.3kV

Module size: Not to scale

SiC
LV100 (750A→800A)
Dual

10.71→11.4 A/cm²

SiC introduction

IGBT
LV100 (600A)
Dual

8.57 A/cm²

Package improvement

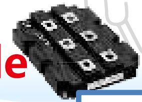
X-series
(1800A)
Single

6.77 A/cm²

R-series
(1500A)
Single

5.64 A/cm²

H-series
(1200A)
Single



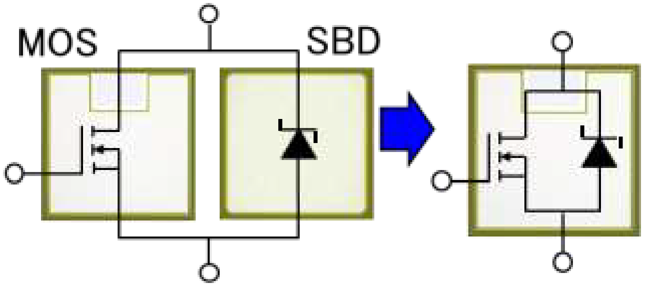
4.51 A/cm²

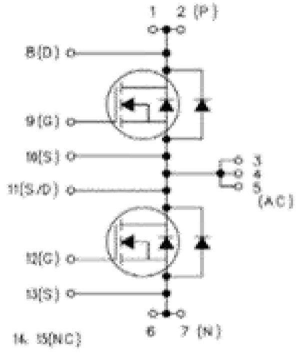
IGBT chip improvement

R-Series

X-Series

3rd gen. SBD embedded MOS





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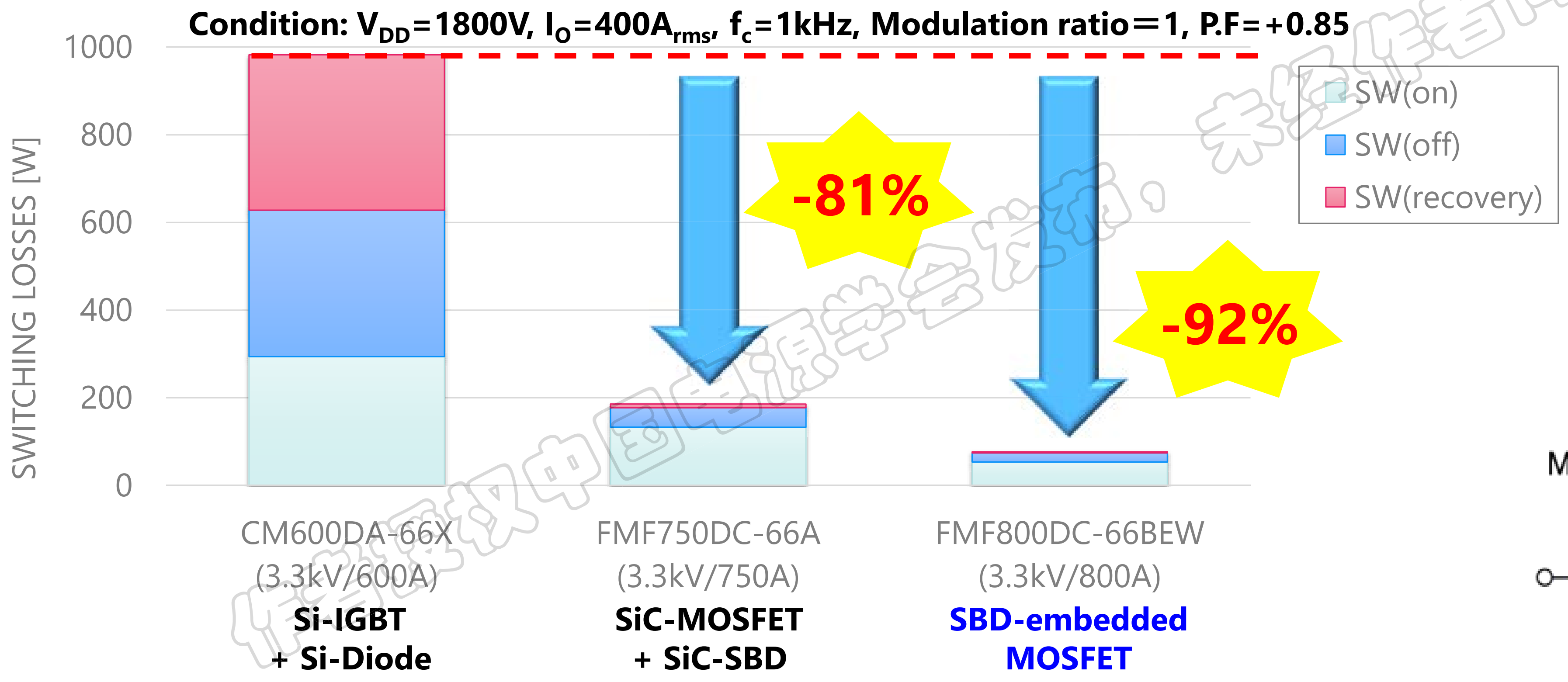
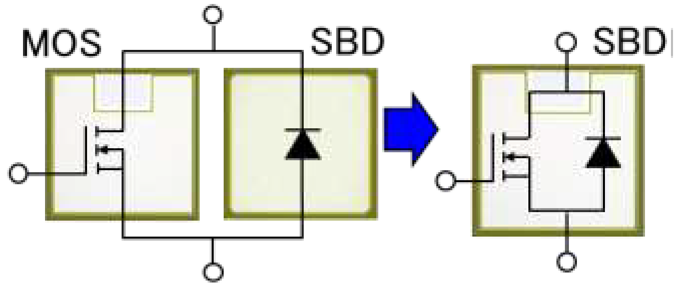
✓ 3.3kV SBD-embedded SiC MOSFET module "Unifull™" series

✓ **Uni**polar device (MOSFET) , **Uni**-chip (SBD embedded), and **Full**-SiC module

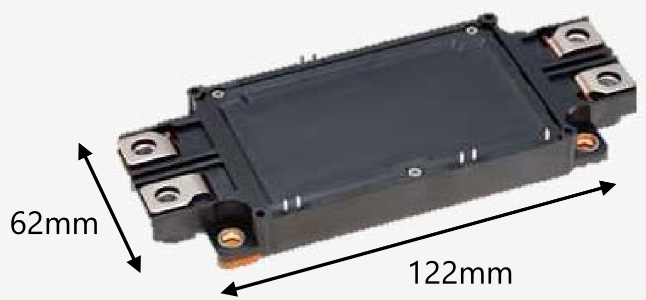


3rd gen. SBD embedded MOS



Low inductance SiC NX power module

To enable high speed operation, low inductance SiC module was developed.



FMF600DXE-34BN
FMF600DXE-24BN

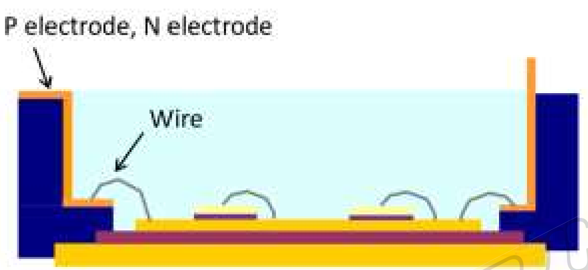


Fig. Conventional PKG.

Ls: 17nH

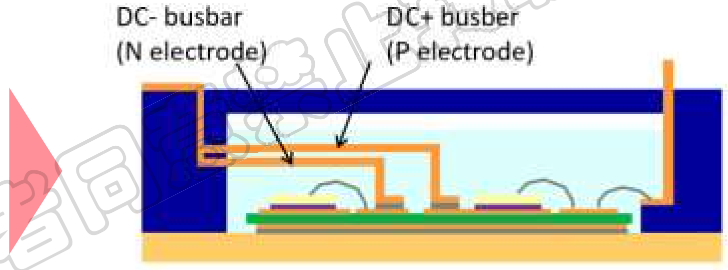
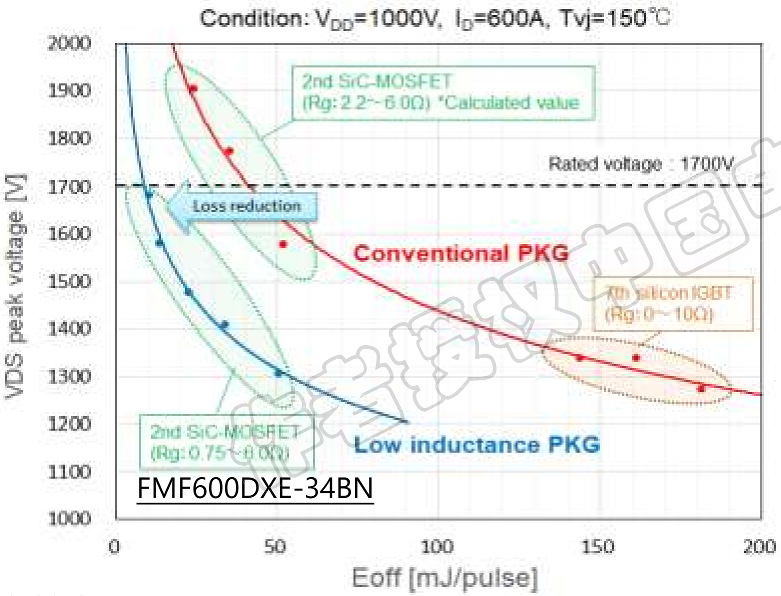
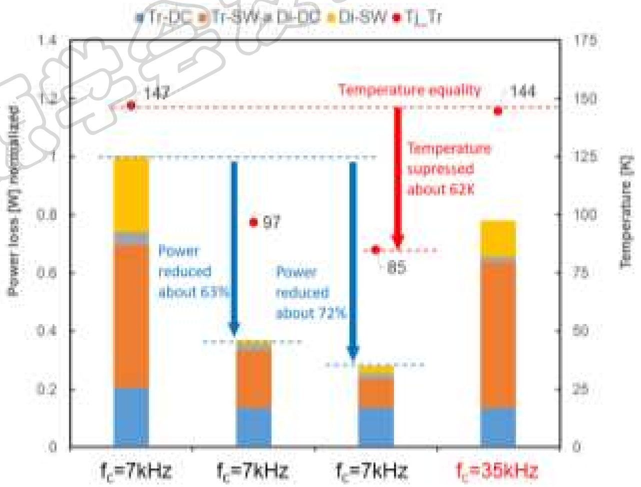


Fig. New Concept PKG.

Ls: 9nH



FMF600DXE-34BN



chip	7th Si-IGBT	2nd SiC-MOSFET	
package	Conventional NX		Low inductance NX

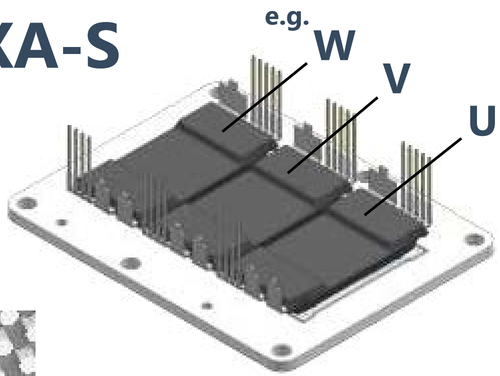
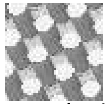
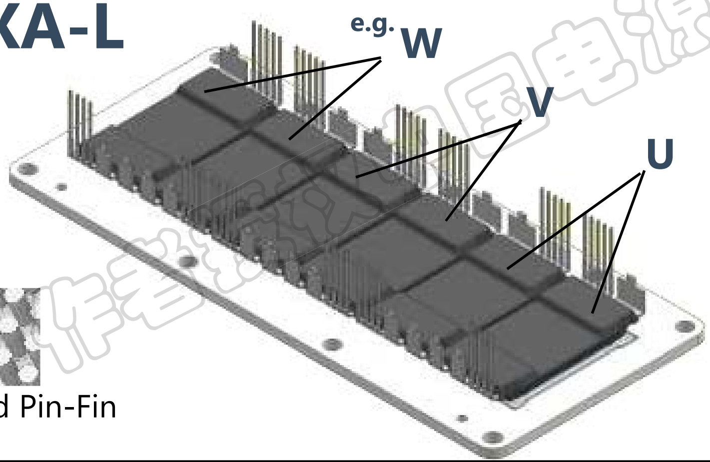
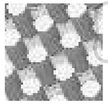
Condition : V_{DD}=900V, I_c=300Apeak, R_g=min, PF=0.8, Modulation=1, T_w=50K, $R_{th(j-c)}$=0.008K/kW, $R_{th(c-s)}$=0.05K/kW

FMF600DXE-34BN

- ✓ Low internal inductance with general package
- ✓ High efficiency 2nd gen. SiC MOSFET
- ✓ High speed switching

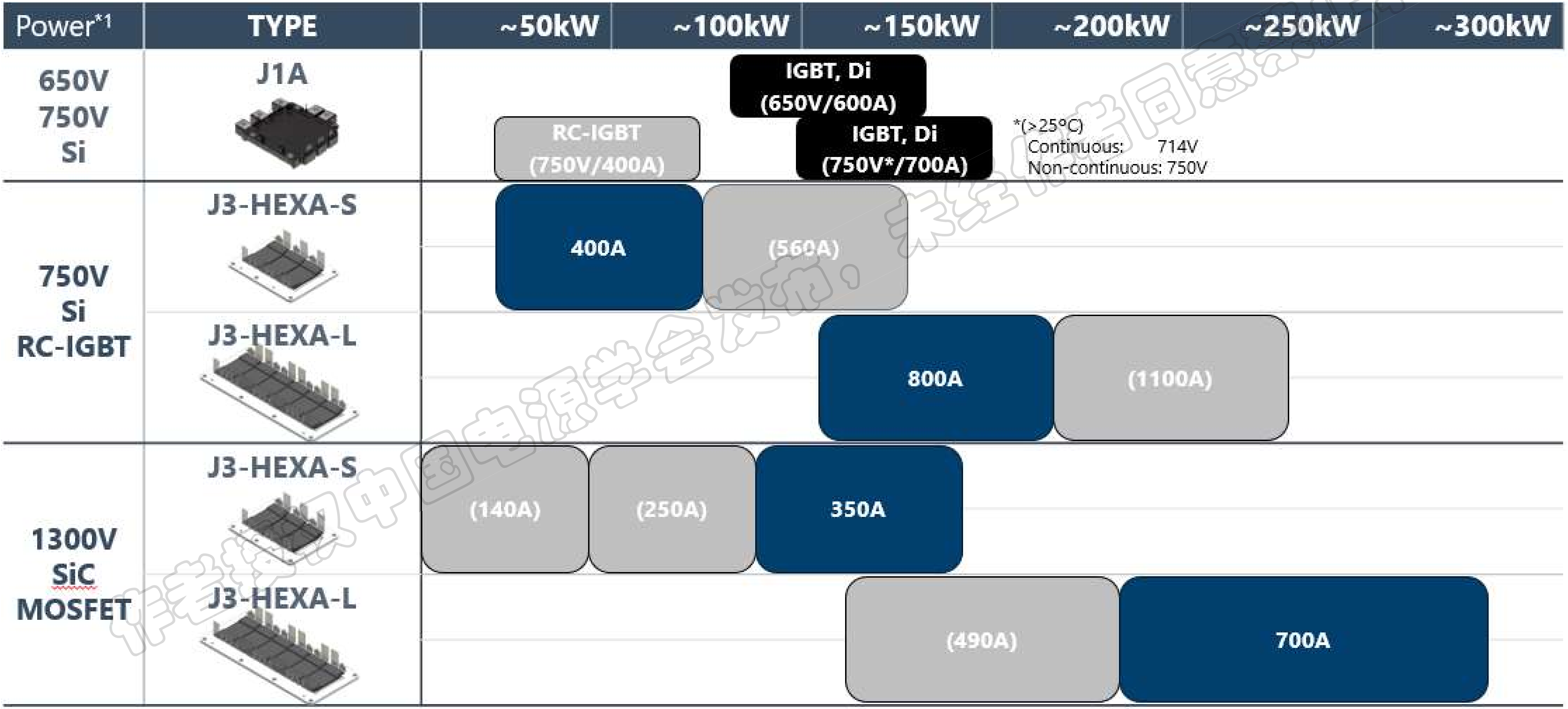
Automotive Modules with RC-IGBT/SiC

- High scalability with 3rd gen. RC-IGBT/4th gen. SiC MOSFET, and parallel use
- Built-in Pin-Fin

Outlines	Configuration	Device	Voltage	Current	Part Number
J3-HEXA-S   Integrated Pin-Fin	6in1 for 3phase inv.	SiC MOSFET	1300V	**350A**	CTF350CJ3C130
		Si RC-IGBT	750V	**400A**	CT400CJ3C075
J3-HEXA-L   Integrated Pin-Fin	6in1 for 3phase inv. (2pcs T-PM in parallel/phase)	SiC MOSFET	1300V	**700A**	CTF700CJ3D130
		Si RC-IGBT	750V	**800A**	CT800CJ3D075

Automotive Modules with RC-IGBT/SiC

- High scalability with 3rd gen. RC-IGBT/4th gen. SiC MOSFET, and parallel use
- Built-in Pin-Fin



*1: Estimation, depends on motor conditions. These lineups may be subjected to change.

Progress of IPM : SLIMDIP with RC-IGBT

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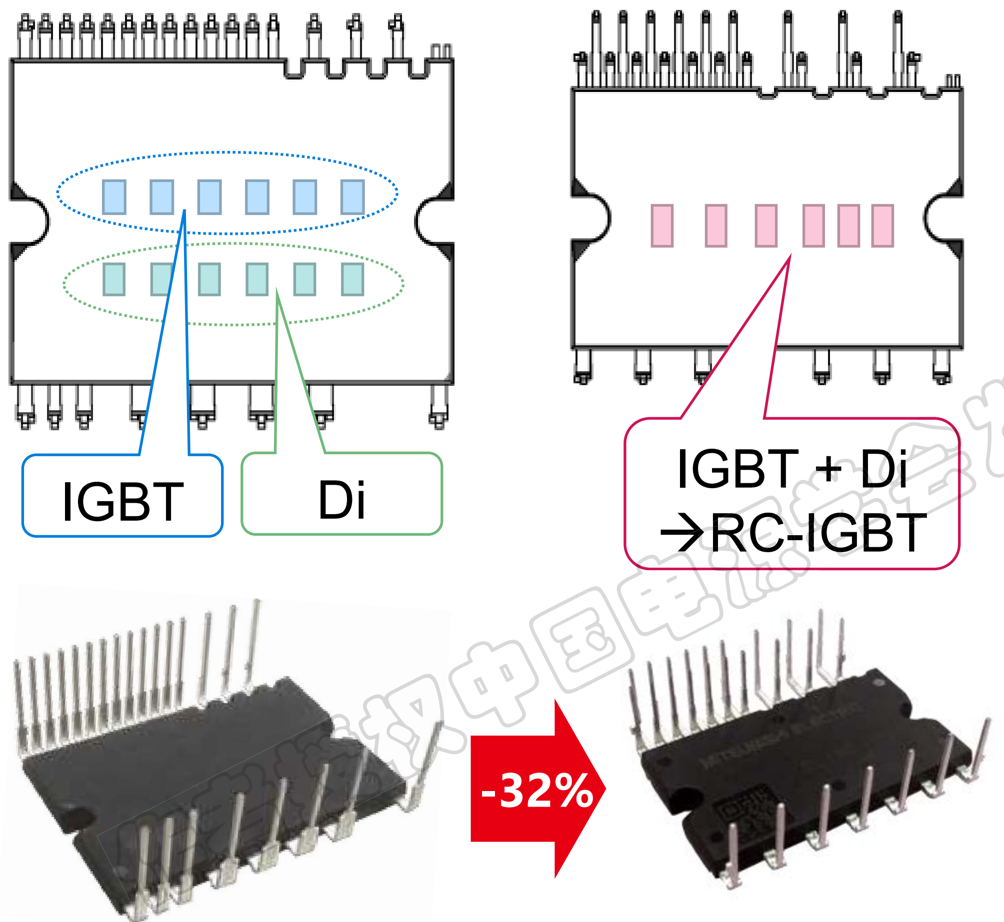
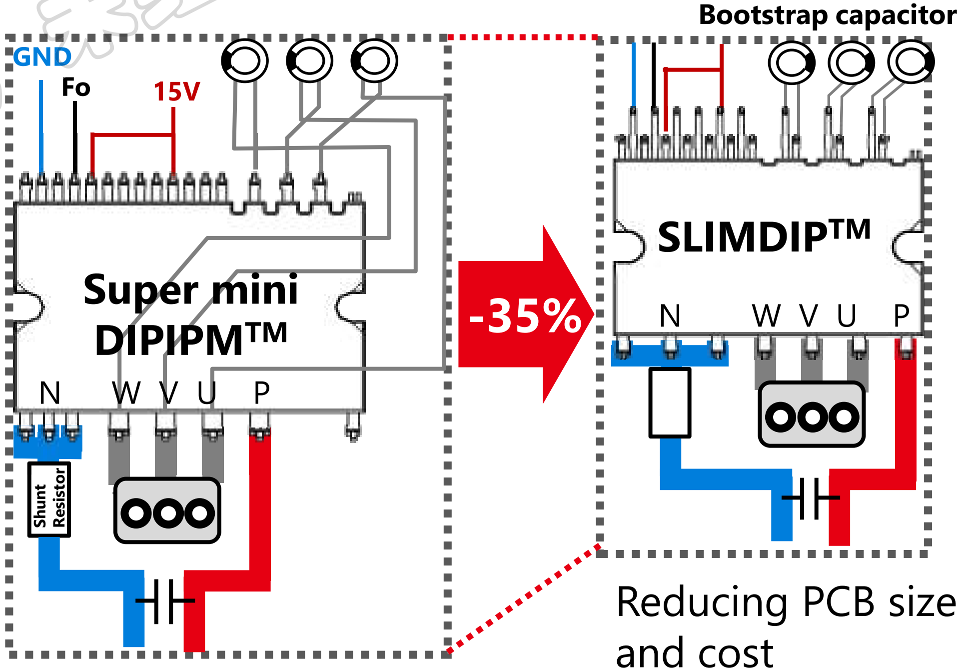
Super mini DIPIPM™ **SLIMDIP™**



24 x 38 (mm) **18.8 x 32.8 (mm)**

- **System size & cost reduction**
- **Shorter design time**

PCB layout



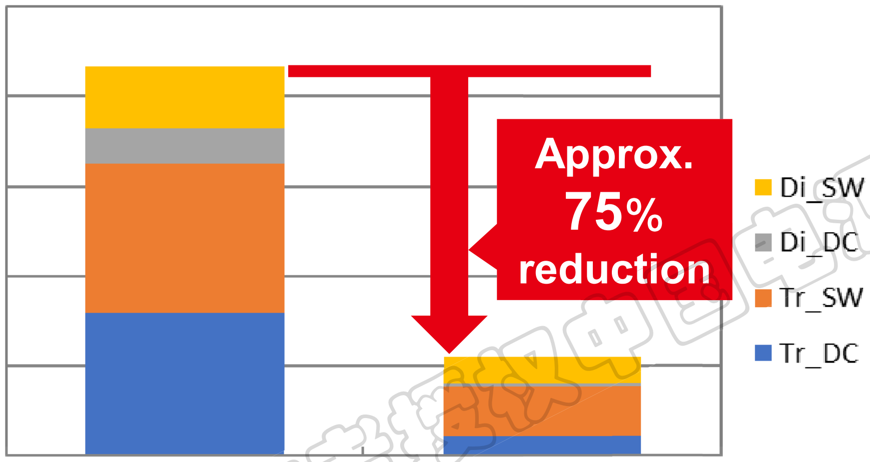
Reducing PCB size and cost

Easy switch from IGBT super mini DIPIPM to full SiC version.

- *Compatible package with IGBT Super mini DIPIPM*

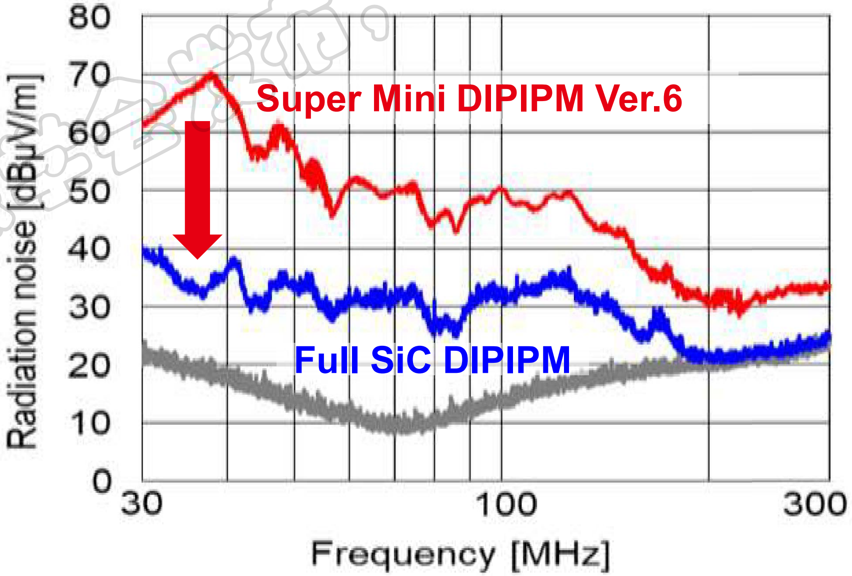
24 x 38 mm

Total Loss

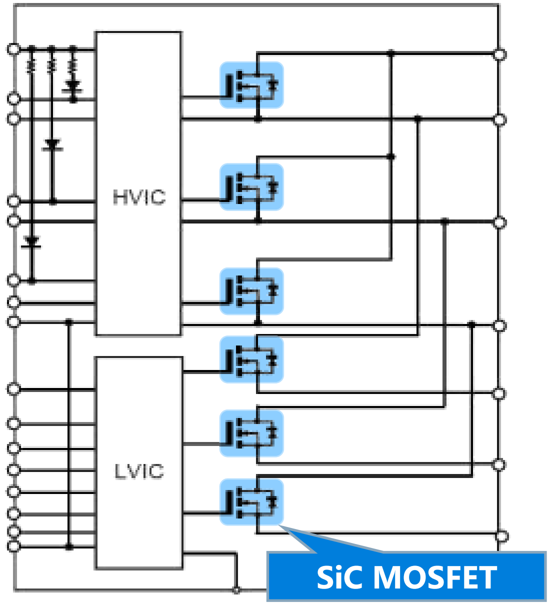


■Conditions: Vcc=300V, VD=18V(SiC) /15V(Si), fc=5kHz, Io=1Arms, PF=0.95, M=0.8, Sinusoidal, Tj=125°C

Low Noise characteristics



Internal Block Diagram



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05

Split-gate IGBT technology and 8th gen. Power Module

LV100

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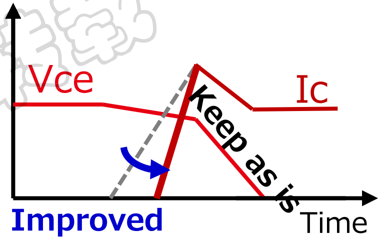
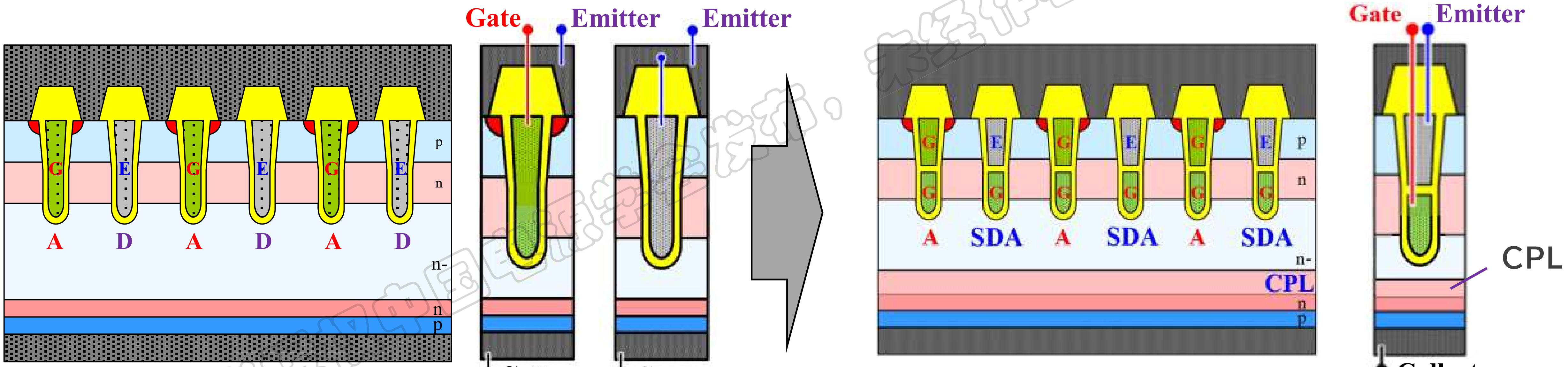
The 8th gen. IGBT adopted “SDA*1 gate structure” and “CPL*2 structure”.

*1 SDA: Split Dummy Active
*2 CPL: Controlling charge carrier Plasma Layer





7th gen. CSTBT™

Active trench (A)

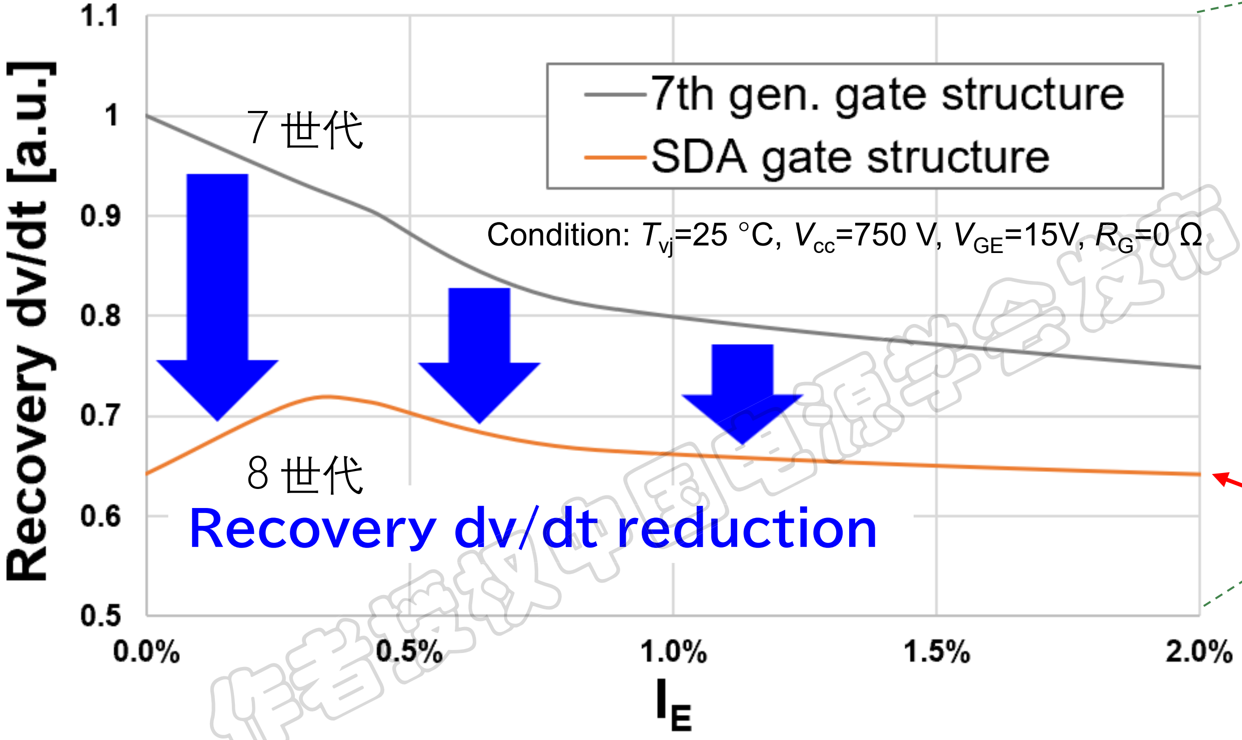
Dummy trench (D)

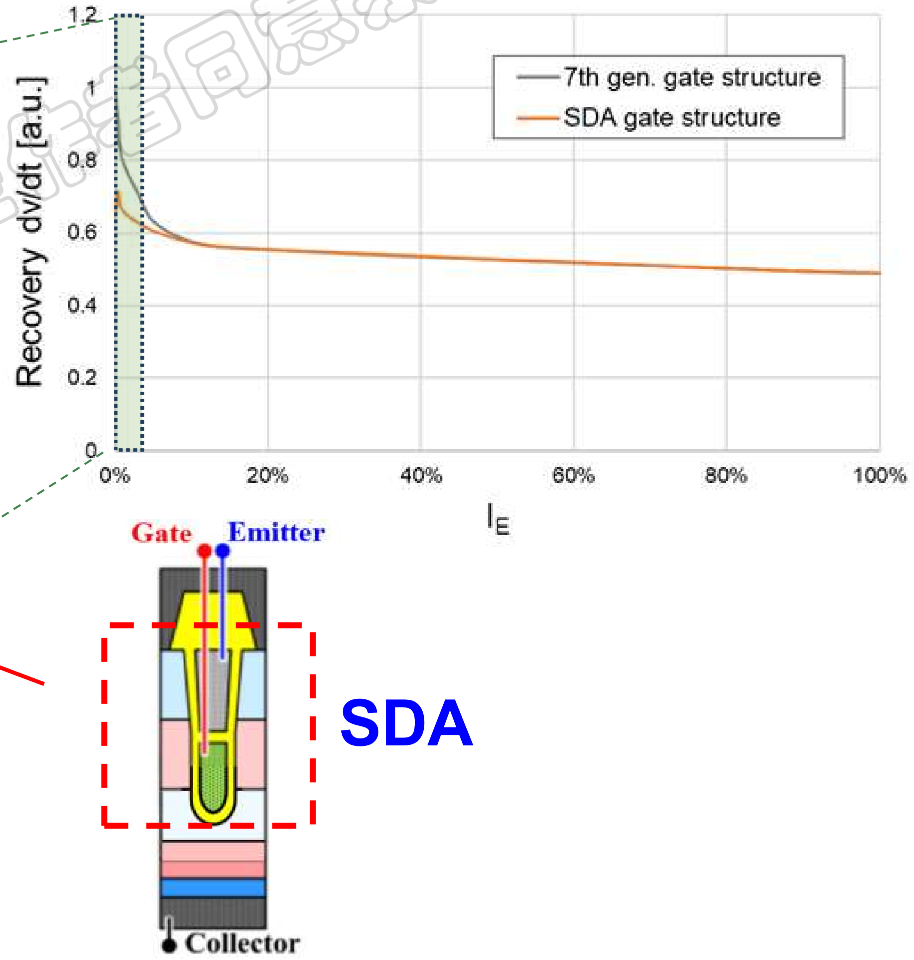
8th gen. CSTBT™

Split Dummy Active trench (SDA)

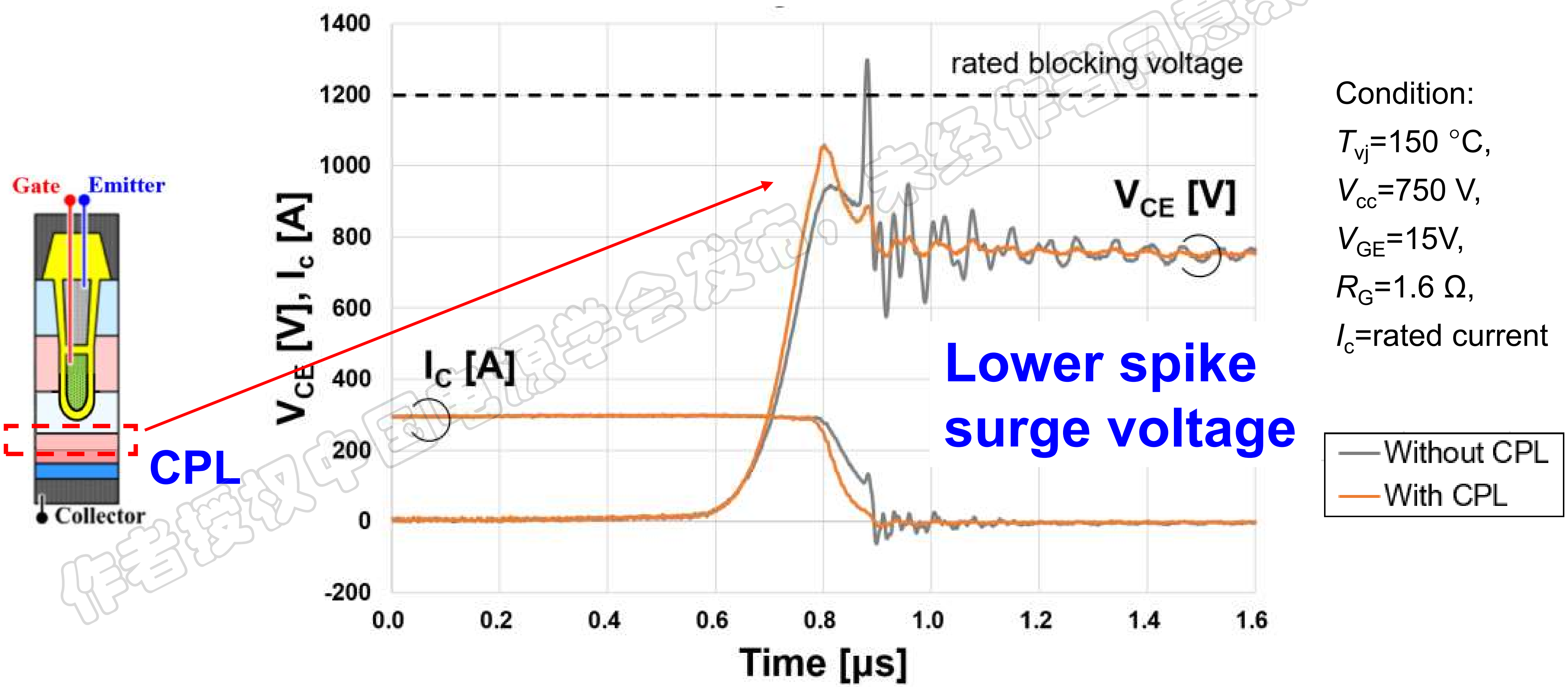
K.Konishi et al., ISPSD2022, Vancouver „Split-Dummy-Active CSTBT™ for Improving Recovery dV/dt and Turn-on Switching Loss Trade-off “

SDA reduces the high recovery dv/dt at low currents, which was the limiting factor to keep the dv/dt within allowable range. Mid-to-high current recovery dv/dt remains the same.





CPL structure can suppress the turn-off surge voltage and oscillation.



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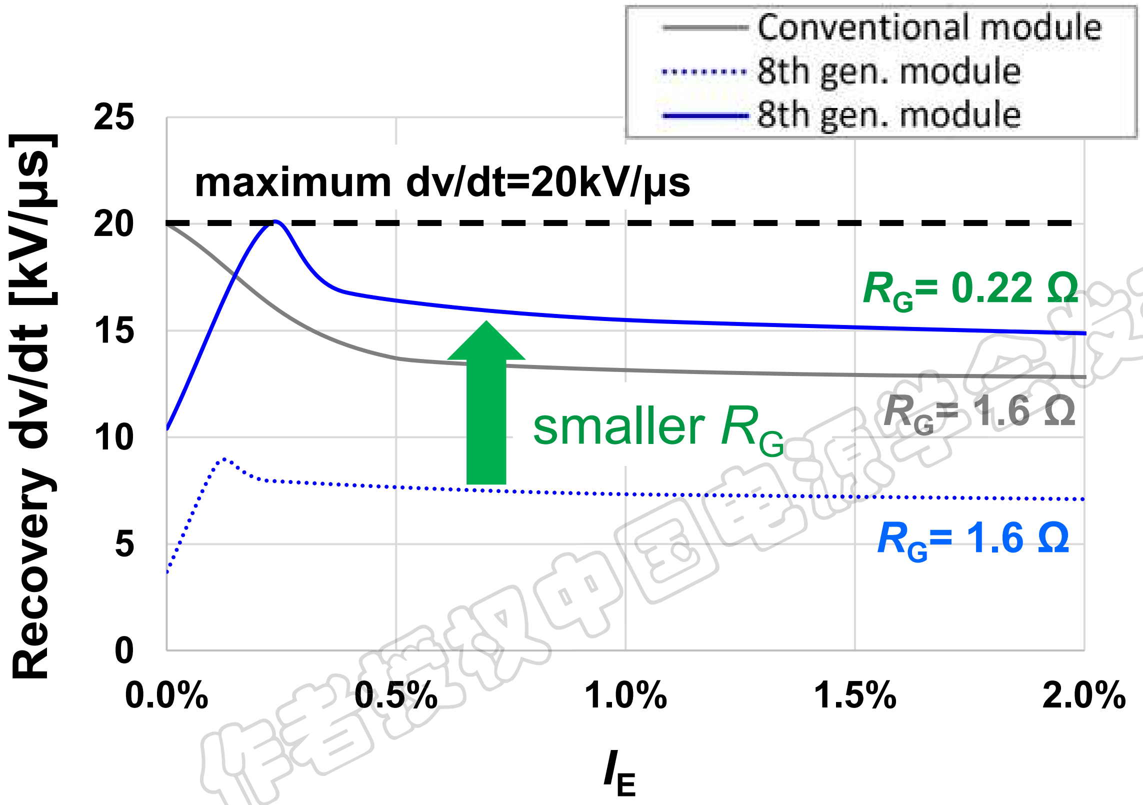
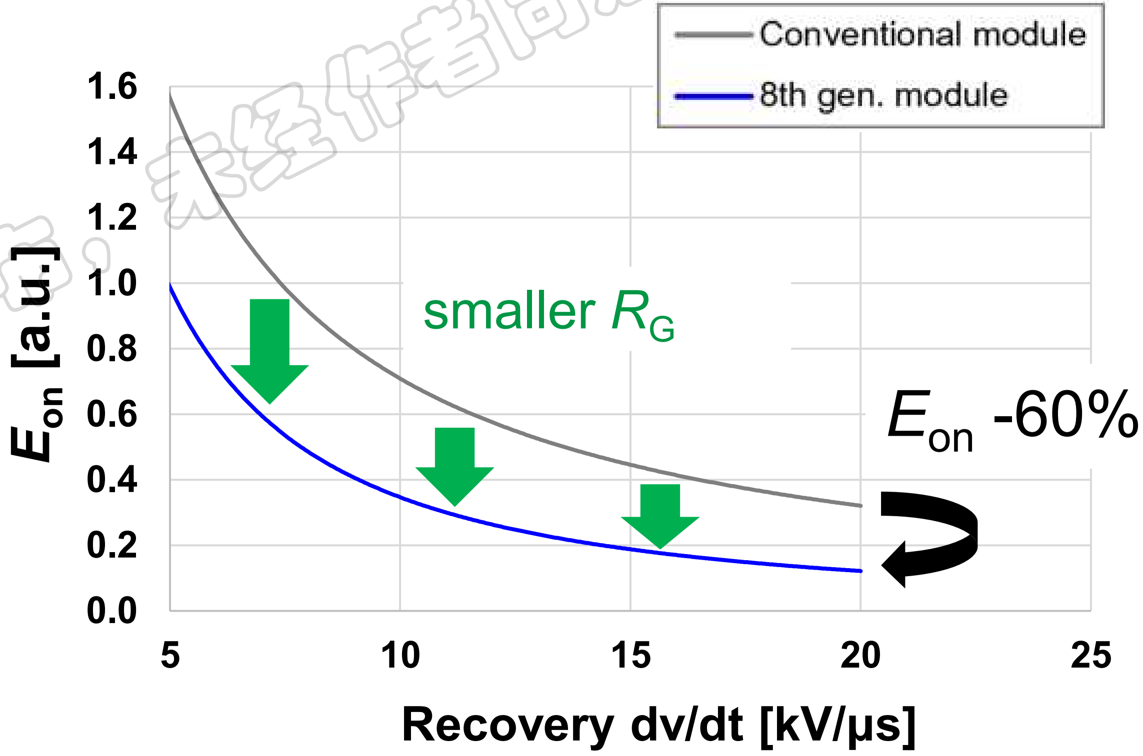
- Thanks to SDA and CPL, Rg can be reduced without sacrificing dv/dt and surge, enabling high-speed switching operation.
- This can reduce Turn-on switching energy per pulse (Eon) by 60%



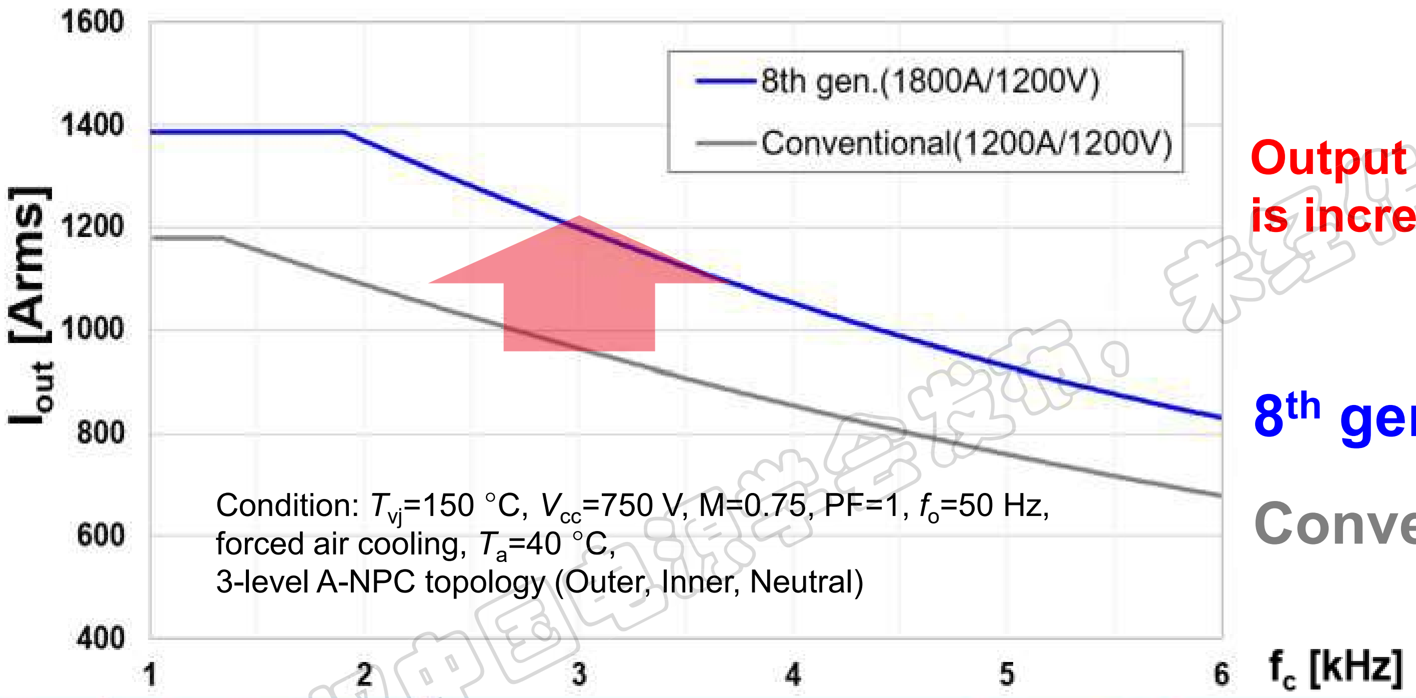
Condition: T_{vj}=25 °C, V_{cc}=750 V, V_{GE}=15V



Condition: T_{vj}=150 °C, V_{cc}=750 V, V_{GE}=15 V, I_C=1800 A, dv/dt=20 kV/μs

Output Power Enhancement

- Thanks to 8th IGBT AC performance and larger chips, the 8th gen. 1200V IGBT power module can achieve 25% more output power



Output power of 8th gen. IGBT module is increased by 25%.

8th gen. module

Conventional

Series	Dimension [mm]	Current [A]						
		≦800	800	1000	1200	1400	1600	1800
LV100	100×140		✓		✓			✓
		Conventional				8th gen.		

06 Summary

- IGBT and SiC are key components for the energy-wise application
- Progress in IGBT and SiC chips has been demonstrated
- Advancements in IGBT and SiC modules, as well as IPMs, have been presented
  ex.
  - LV100 SiC → Unifull™ Series (3.3kV 200-800A)
  - LV100 Si → 8th gen. IGBT with 25% increased output power

- We will continue to contribute to an energy-wise society with our power devices

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