Towards next generation power module package technology blooming

IDAKA, Shiori / Mitsubishi Electric Europe B.V.

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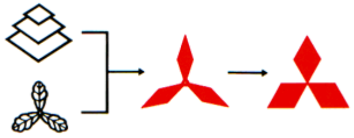
OUTLINE

About Us

The founder, Yataro Iwasaki

Photo courtesy of The Mitsubishi Archives

Mitsubishi Sha was established. It promoted its business diversification and grew as a modern corporation.



Origin of the Three-Diamond Mark

100th anniversary in 2021

Mitsubishi Electric Corporation was established.

1870 – Tsukumo Shokai, which was the origin of Mitsubishi, was established.

1886 – Mitsubishi Sha was established. It promoted its business diversification and grew as a modern corporation.

1917 – Spinning-off of the business departments started.

Mitsubishi Goshi Kaisha became a holding company.

1921 – Mitsubishi Electric Corporation was established.

1946 – Mitsubishi Headquarters was dissolved.

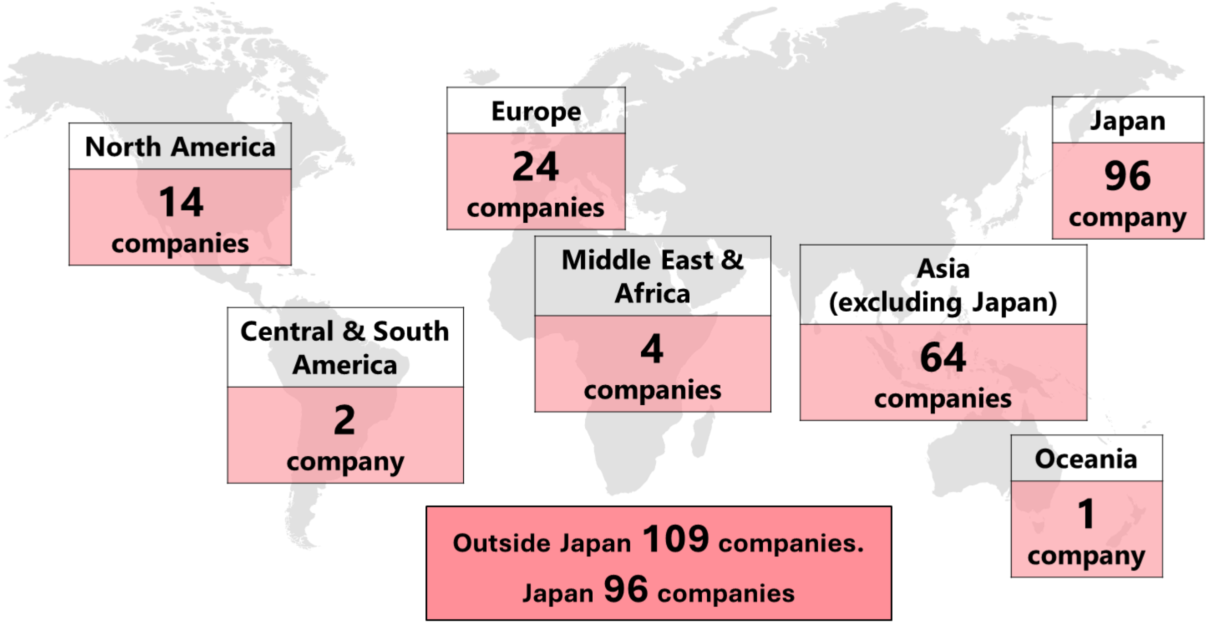
Each Mitsubishi company started as a new independent entity.

Mitsubishi Electric Corporation is an independent company like other Mitsubishi companies, and is separately owned, managed, and operated.
With the exception of other companies in the Mitsubishi Electric Group, it bears no legal affiliation with other companies that have the word "Mitsubishi" in their names.

About Us

Head Office Location:	Tokyo Building, 2-7-3 Marunouchi, Chiyoda-ku, Tokyo 100-8310, Japan
President & CEO:	Uruma Kei（Inaugurated on July28, 2021）
Established:	January 15, 1921
Revenue:	¥4,191,443 million
Paid-in Capital:	¥175,820 million
Shares Issued:	2,147,201,551 shares
Total Assets:	¥4,797,921 million

（As of March 31, 2021）



PRODUCTS & SERVICESOF MITSUBISHI ELECTRIC CORP.


BUILDING SYSTEMS

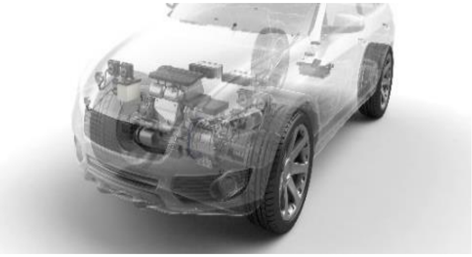

ENERGY SYSTEMS


TRANSPORTATION SYSTEMS


HOME PRODUCTS


AIR CONDITIONING SYSTEMS

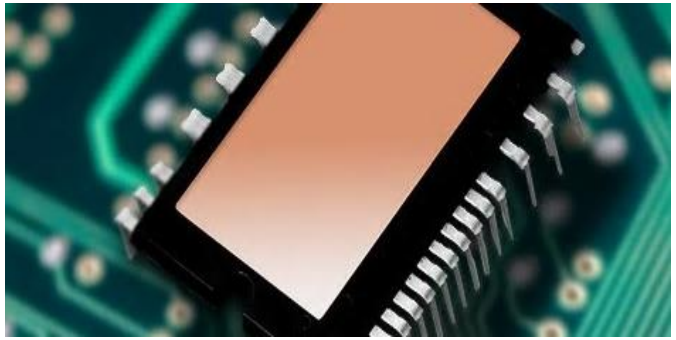

FACTORY AUTOMATION SYSTEMS

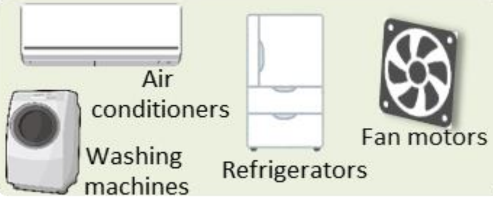
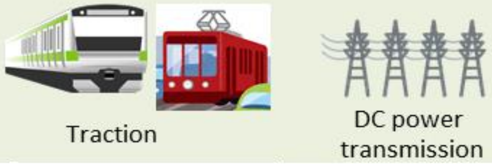

AUTOMOTIVE EQUIPMENT


PUBLIC SYSTEMS


SPACE SYSTEMS

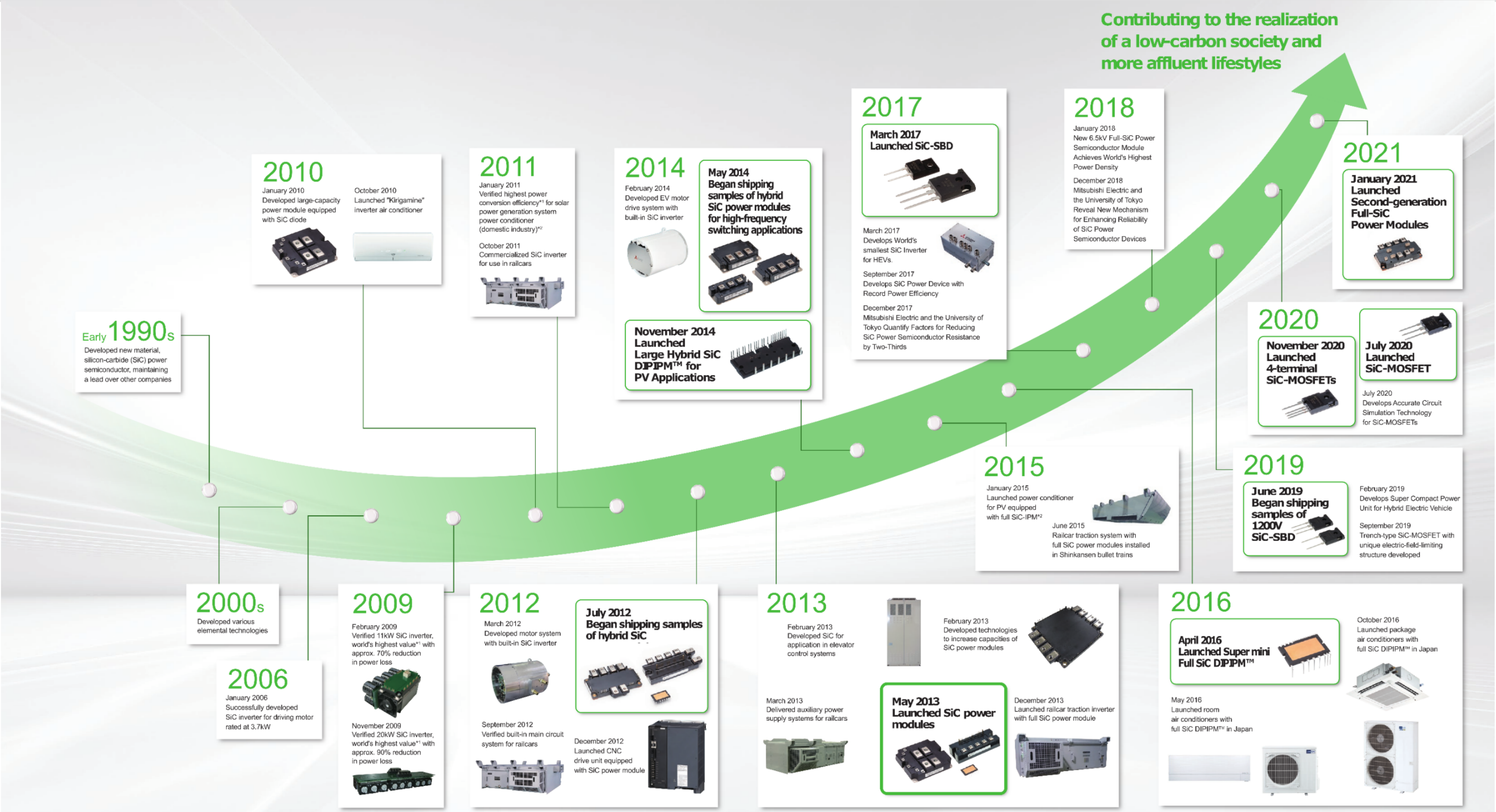

INFORMATION/COMMUNICATION SYSTEMS


SEMICONDUCTORS/DEVICES

Application segment	Application examples	IGBT and SiC module: Case type – General	IGBT and SiC module: Case type – HV	IGBT and SiC IPM: Case type	IGBT and SiC IPM: DIP type	Discrete
Home appliances						
Industry (including renewable energy)						
Traction/ Electric power						
Automotive						

IPM: Intelligent Power Module

MITSUBISHI ELECTRIC
Changes for the Better



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).
* The year and month listed are based on press releases or information released during the product launch month in Japan.

*1 Researched in press releases by Mitsubishi Electric.
*2 Mitsubishi Electric solar-power generation system discontinued on March 31, 2020.

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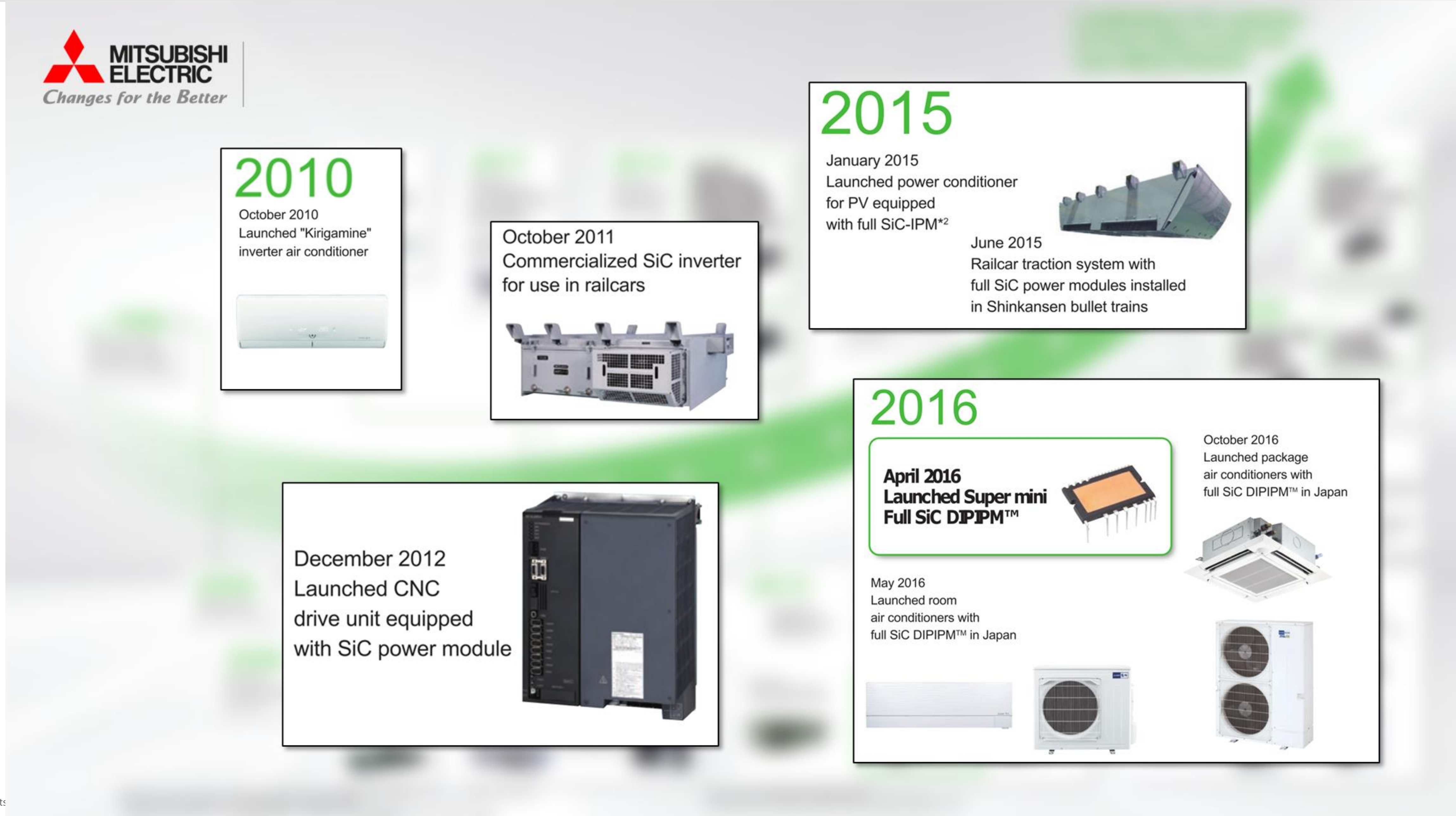
Changes for the Better



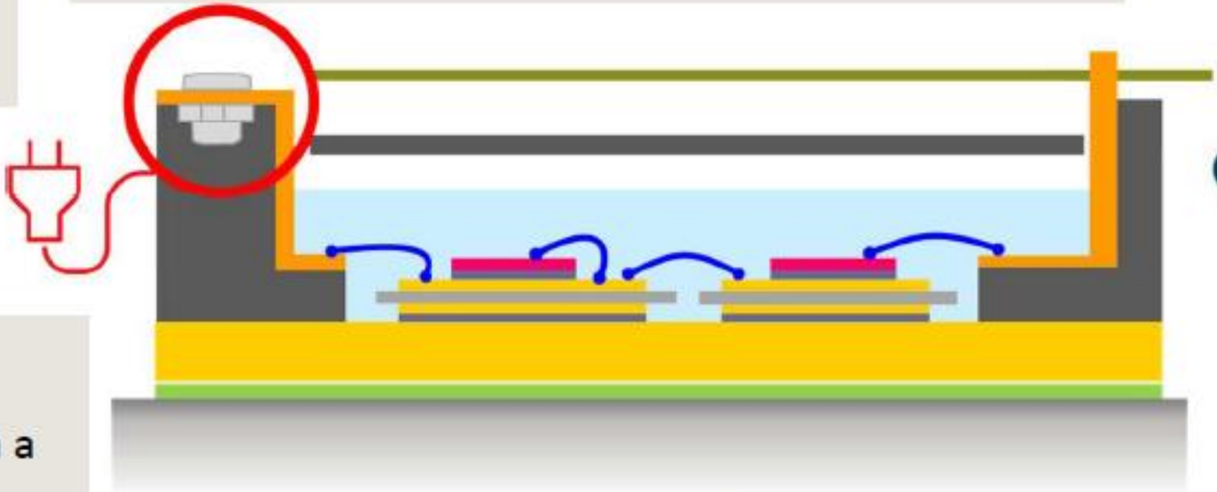
01

Introduction

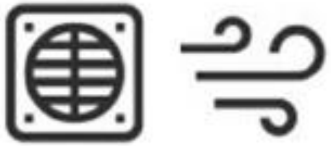
What is packaging?

Interface
To connect semiconductors to outside systems mechanically and electrically.

Protection
To protect semiconductors from external influences (stress, electrostatic, chemicals, humidity, dust…)

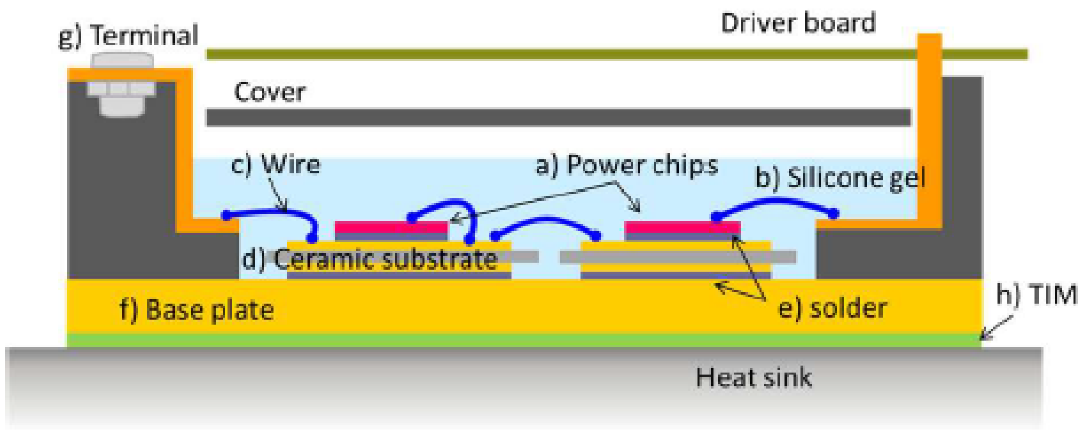


Modularization
To configure the desired “switch” with a combination of multiple semiconductors in standard outlines.



Thermal management
To dissipate the heat generated in semiconductors to the outside

Introduction



parts	material	function
a) Power chips	Si, SiC etc	Switching
b) Silicone gel	Silicone	Protect power chips
c) Wire	Al, Al-alloy	Current flow
d) Ceramic substrate	Ceramics with Cu, Al	Electrical insulation Current flow Thermal transfer
e) Solder	Sn-alloy	Mechanical joint Current flow Thermal transfer
f) Base plate	Cu	Thermal transfer Housing
g) Terminal	Cu	Current flow
h) TIM	Silicone, epoxy	Thermal transfer
i) case, cover	Engineering plastic	Housing Holding the terminals

Transmission and distribution

HVDC

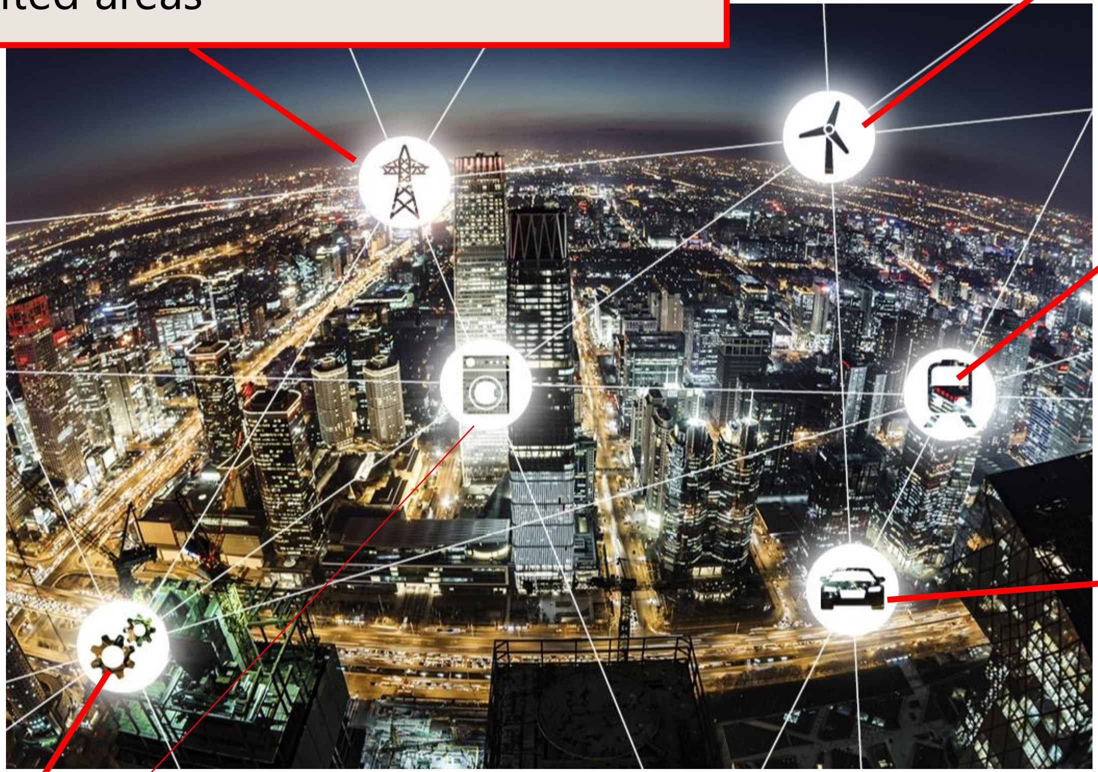
Long-distance transmission through uninhabited areas

Renewables

Installed in harsh environments

Offshore wind, Floating Solar, SPS in desert

ESS in uninhabitable areas, etc



Railway

Expansion of coverage area

Expansion of vehicle variants

Installation of inverters outside the vehicle

Automotive

Expansion of coverage area

Expansion of vehicle variants

Industrial, Home appliance

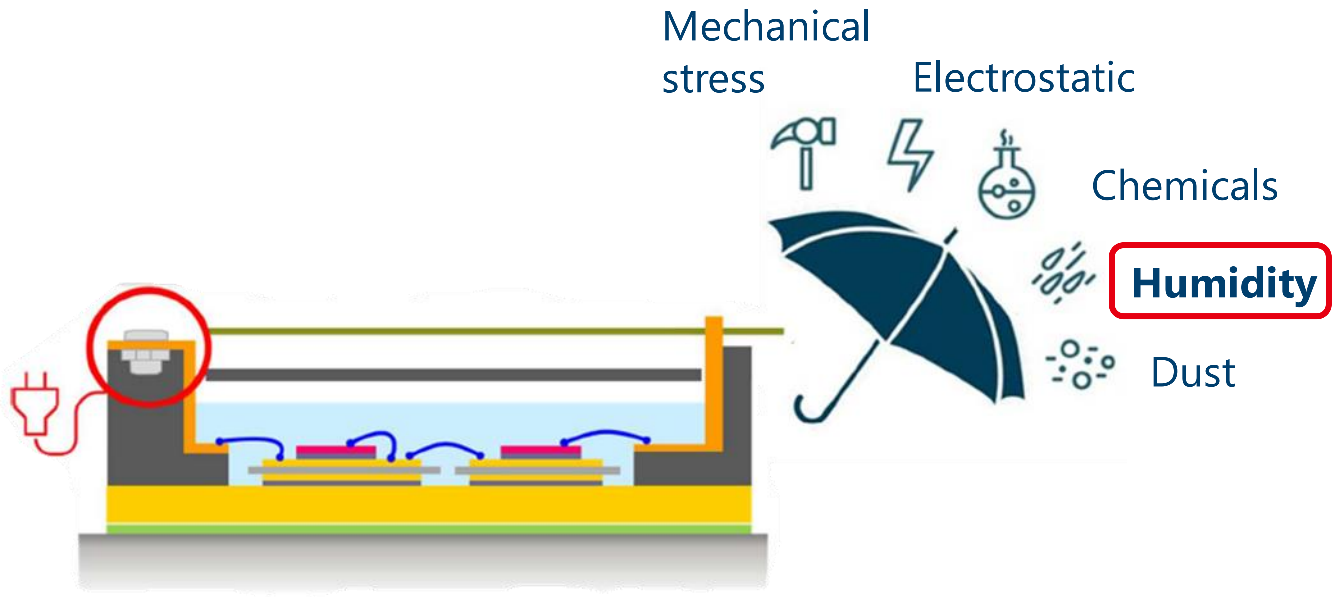
Expansion of coverage area

power modules are expanding their applications

↓

coming into use ***outdoors*** and **in harsh environments**

Power modules are beginning to be used ***outdoors*** and **in harsh environments** ➡



What impact does humidity have?

Demands for "**NEW**" reliability

Test & models

- Failure Mechanism
- Accelerated testing
- Lifetime prediction and modelling

Power chips

- Highly protective materials
- Additional protection
- Highly robust structure

Package

- Highly protective materials
- Additional protection
- Highly robust structure

02

Tests and Models

H3TRB Test

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Changes for the Better

High Humidity High Temperature Reverse Bias (H3TRB) test

1000hr	
85°C, 85%rH	
80% ($V_{CE\ max}$, $V_{DE\ max}$, $V_{R\ max}$), **max 80V**	IEC 60749-5:2017

without depending on the blocking voltage of the devices!

New

High Voltage High Humidity High Temperature Reverse Bias (HV-H3TRB) test

1000hr		
85°C, 85%rH		
variant 1 80V	Variant 2 **80% ($V_{CE\ max}$, $V_{DE\ max}$, $V_{R\ max}$)**	ECPE Guideline AQG324 Qualification of Power Modules for Use in Power Converter Unit in Motor Vehicles

Voltage class		1700V	3300V	4500V	6500V
HV-H3TRB test		**1000V**	**1950V**	**3000V**	**3900V**
U_n	Nominal line voltage	750V	1500V	-	3000V
U_{max1}	Highest permanent DC catenary voltage	900V	1800V	-	3600V
U_{max2}	Highest non-permanent DC catenary voltage	1000V	1950V	-	3900V
U_{max3}	Highest temporary over-voltage	1270V	2540V	-	5075V

ECPE Guideline PSARRA01
Railway Applications H3TRB tests for Power Semiconductor

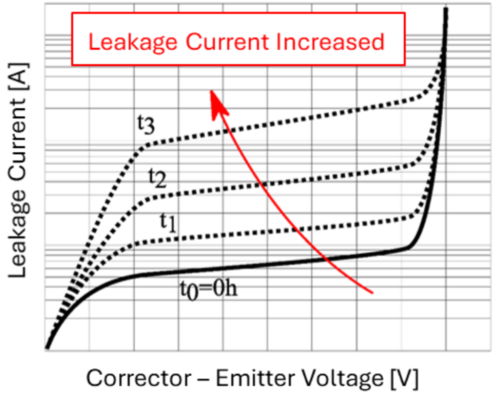
High bias voltages must be applied considering the ***real*** environment.

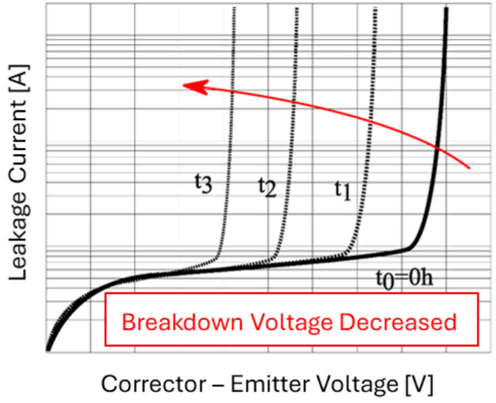
Tests and Models – *Failure Mode*

Degradation of electrical characteristics

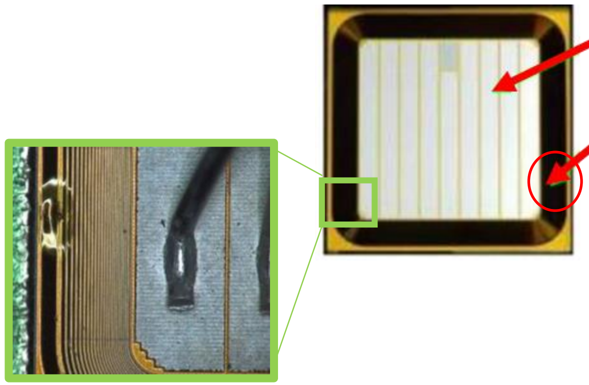
Shown as a combination of ***2*** mode

- ✓ *Leakage Current* ⬆
- ✓ *Breakdown Voltage* ⬇

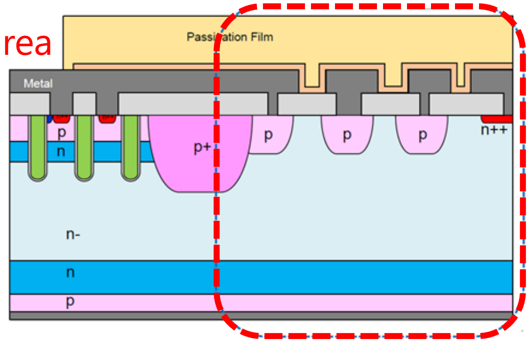




Failure point



Failures can be seen in
Edge termination area → *Determine the breakdown voltage*



Chip edges have a lower breakdown voltage due to electric field crowding

⬇

Edge termination :
Designed to spread localized electric fields

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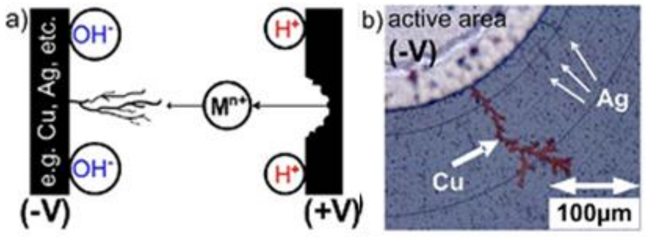
Changes for the Better

1. Electro-chemical metal corrosion

Electro-chemical migration (ECM)

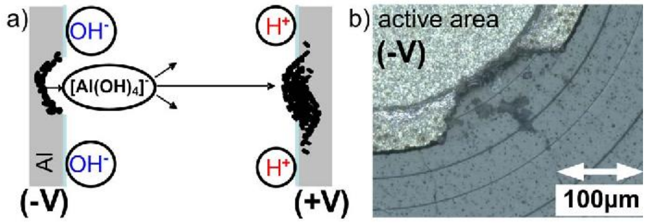
❖Dendritic metal growth from the anode



Aluminum Corrosion

❖Al electrophoresis into the passivation layer

❖Delamination of the passivation layer due to generated gases



Stress factor

- ✓ Relative humidity
- ✓ Temperature
- ✓ Voltage

No interactions between the stresses

Acceleration factor : advanced Peck's model

$$a_f(RH,T,V) = \left(\frac{RH_a}{RH_u}\right)^x \cdot exp\left(\frac{E_A}{k}\cdot\left[\frac{1}{T_u}-\frac{1}{T_a}\right]\right)\cdot\left(\frac{V_a}{V_u}\right)^y$$

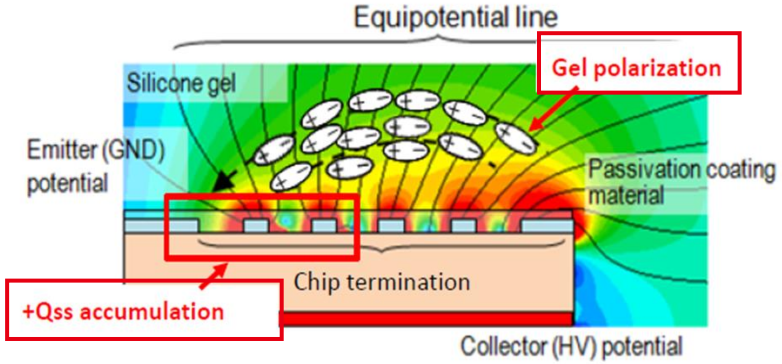
RH : relative humidity
T : temperature (K)
E_A : activation energy
k : Boltzmann's constant
V : voltage (V)

1) Zorn, C., Kaminski, N., et al. : "Acceleration of Temperature Humidity Bias (THB) Testing on IGBT Modules by High Bias Levels", IEEE 2015,

MITSUBISHI ELECTRIC Changes for the Better

New

2. Decrease in avalanche breakdown voltage



Dielectric polarization
+
Moisture absorbing

in Silicone gel

Surface-state charge (Q_{SS}) accumulation

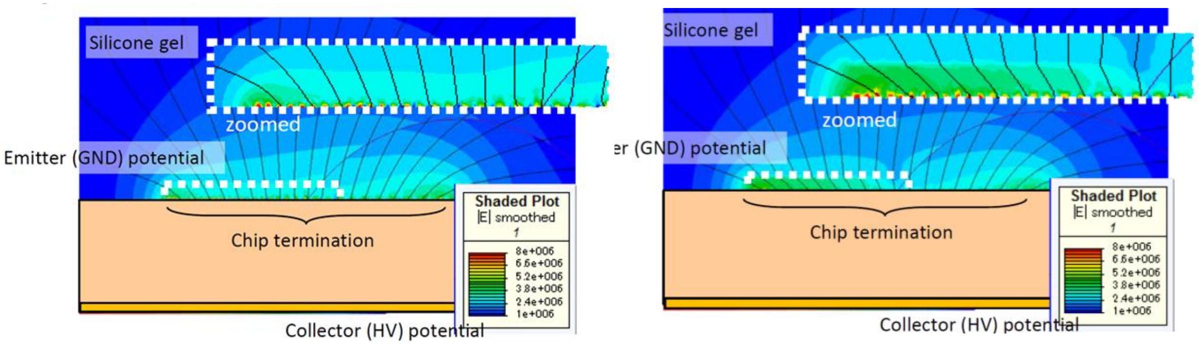
Decrease in blocking capability (higher electric field)

Avalanche breakdown

Edge termination area

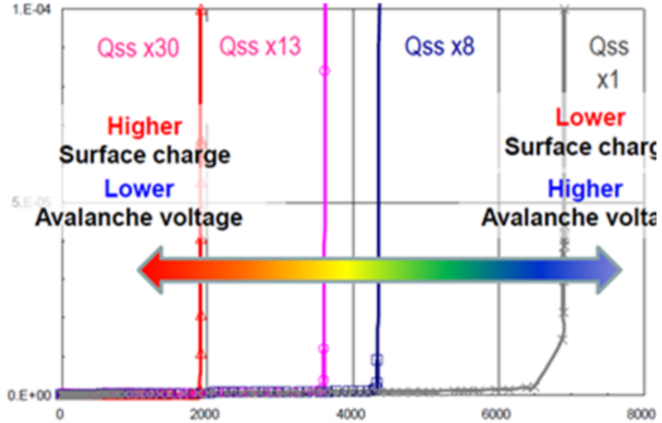
Failure

Higher electric field!



a) Under dry condition (w/o Q_{SS} accumulation)

b) Under moisture-absorbing conditions (w/ Q_{SS} accumulation)



Correlation between avalanche breakdown voltage and Q_{SS}

2) Tanaka, N., Ota, K., et al. : "Robust HVIGBT Module Design Against High Humidity", PCIM 2015, May 2015,

MITSUBISHI ELECTRIC *Changes for the Better*

Acceleration factor : advanced Peck's model

$$a_f(RH,T,V) = \underbrace{\left(\frac{RH_a}{RH_u}\right)^x}_{\pi_H} \cdot \underbrace{exp\left(\frac{E_A}{k}\cdot\left[\frac{1}{T_u}-\frac{1}{T_a}\right]\right)}_{\pi_T} \cdot \underbrace{\left(\frac{V_a}{V_u}\right)^y}_{\pi_V}$$

RH : relative humidity
T : temperature (K)
E_A : activation energy
k : Boltzmann's constant
V : voltage (V)

New

Lifetime estimation

$$LT = \frac{LT_b}{a_f(RH,T,V)} = \frac{LT_b}{\pi_H \pi_T \pi_V}$$

LT_b: base lifetime @ standard condition (as reference value)

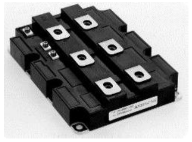
Step 1
parametric THB test (RH, V, T)

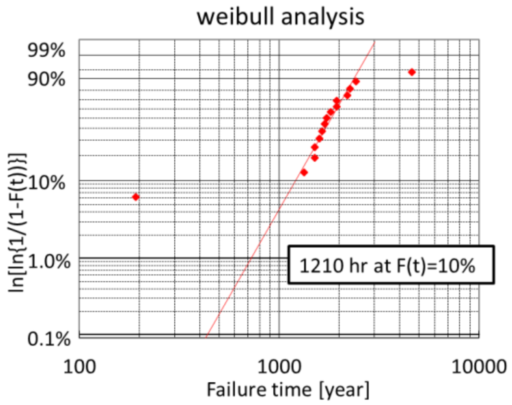
Step 2
parameter fitting (E_A, x, y) → $a_f(RH, T, V)$

Step 3
convert THB results to ref. condition → LT_b

Step 4
Lifetime model

Lifetime model for 3.3kV IGBT module





$x = 20.50$
$y = 1.37$
$E_A = 0.749\ eV$
$LT_b = 1210$ @ 75%RH, 25℃, 1500V

3) Kitajima, Y., Hatori, K., et al. : "Lifetime Estimation Model of HVIGBT Considering Humidity", PCIM 2017,

03

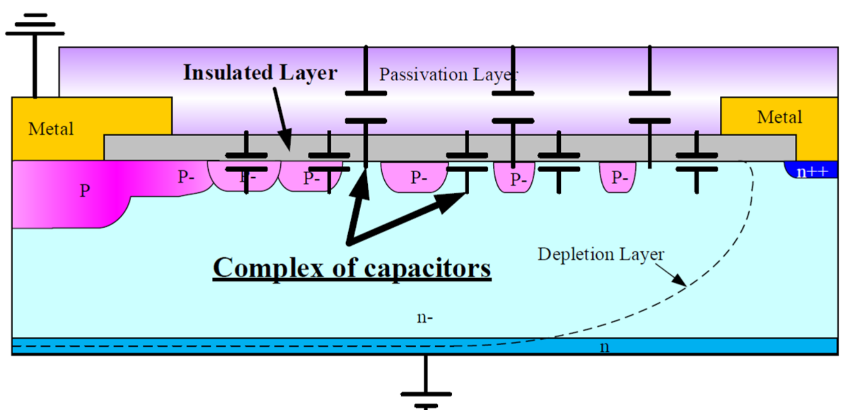
Chip Design

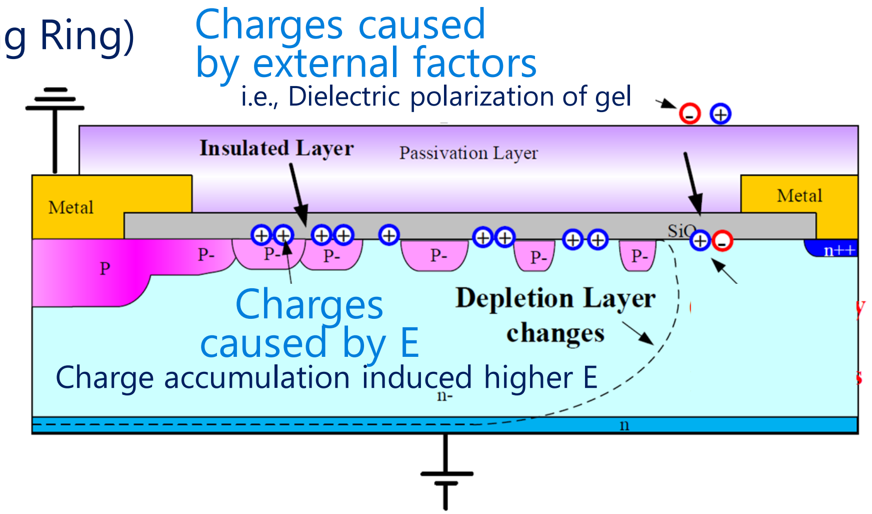
Edge Termination

MITSUBISHI ELECTRIC *Changes for the Better*

Designs of edge termination

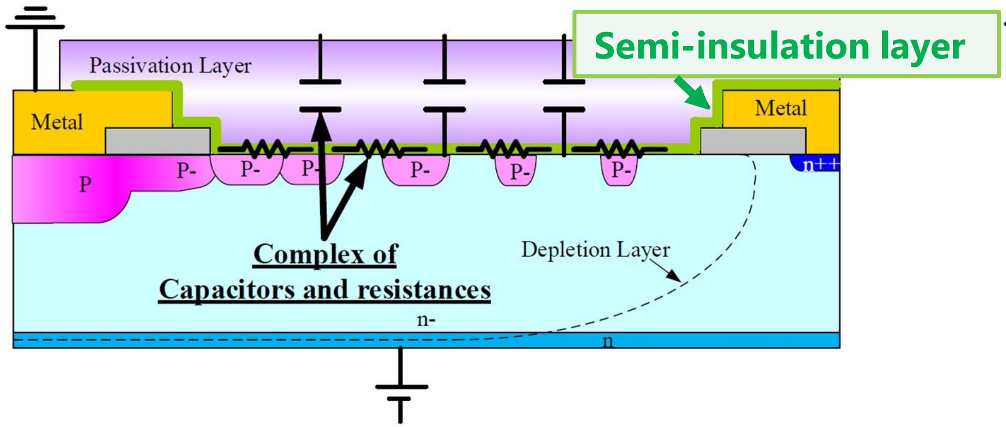
Conventional design : LNFLR (Linearly Narrowed Field Limiting Ring)

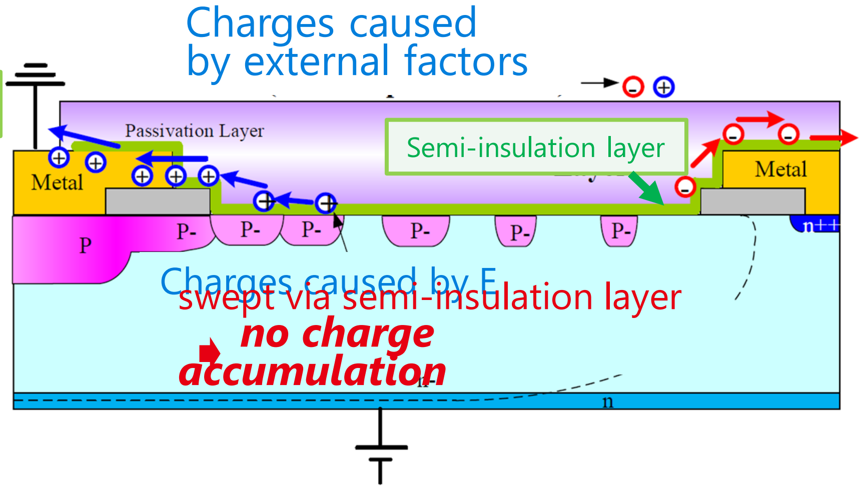




New

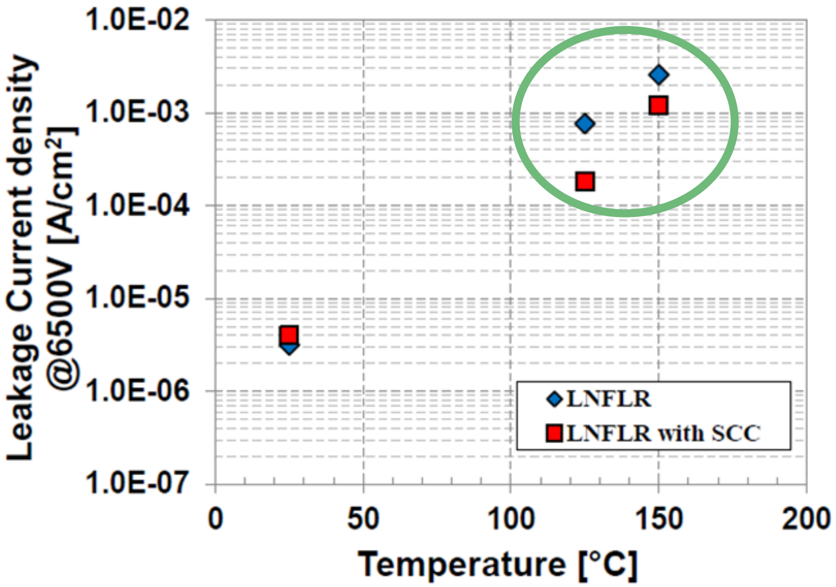
LNFLR with SCC (Surface-Charge Control)



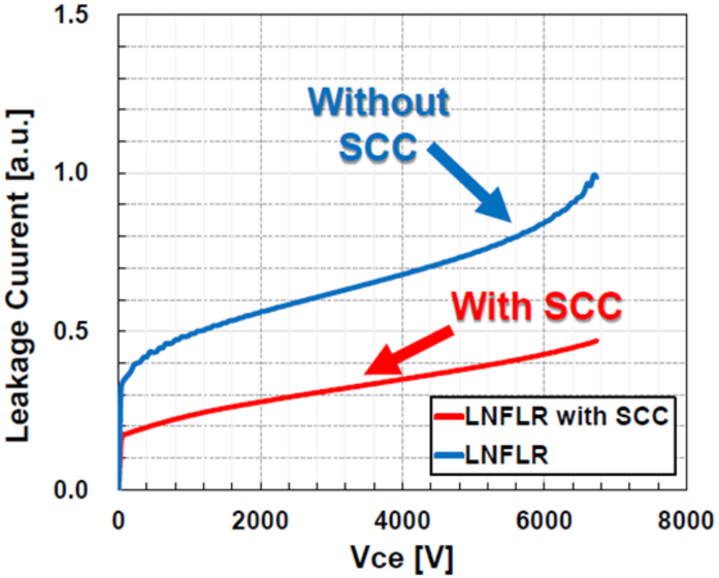


4) Honda, S., Harada, T., et al. : "High Voltage Device Edge Termination for Wide Temperature Range Plus Humidity with Surface Charge Control (SCC) Technology", Proc. ISPSD 2016,

Chip Design – *Effect of SCC*



- Temperature dependence of the leakage current -



- Waveform of the leakage current @150 deg.

Lower leakage current under high temperature

➡ The electric field distribution was balanced with the avoidance of Q_{SS} accumulation

04

Package

Silicone Gel and Passivation

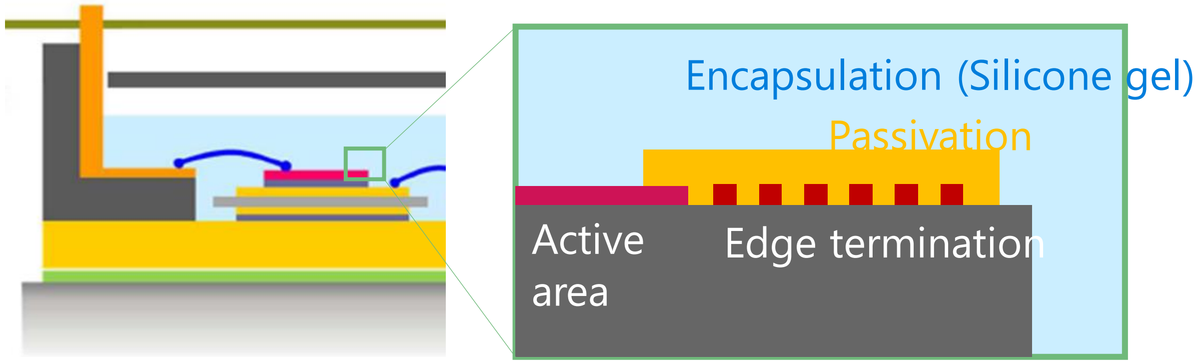
Package

Highly protective materials

- *Silicone gel* : Dielectric polarization
- *Passivation material* : Qss accumulation

Additional protection

Highly robust structure



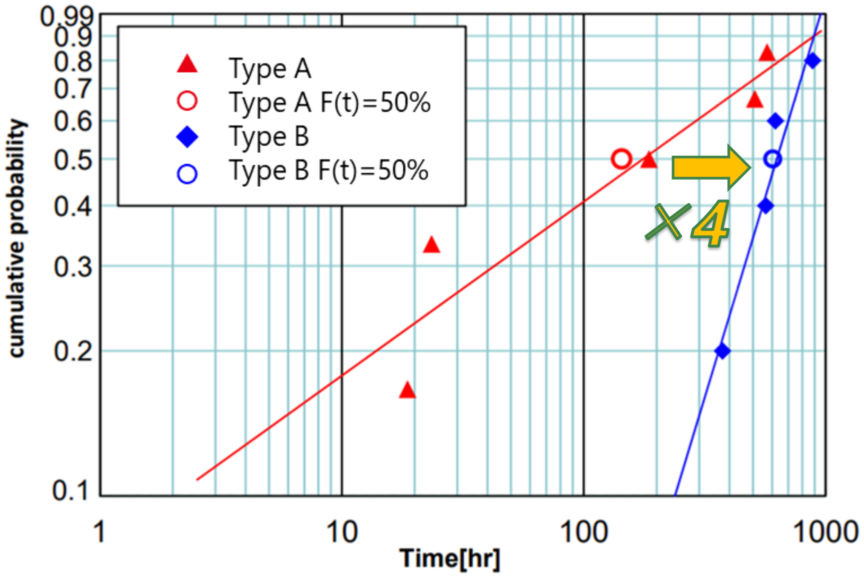
sample	materials	
	Silicone gel	Passivation
Type A (conventional)	A	A
Type B	B	B

HV-H3TRB test :

Ta=85℃ / 95%RH, V_{CE}=4000V(DC), VGE=0V

	Type A (n=5)	Type B (n=4)
DUT 1	18.7 hr	374.8 hr
DUT 2	23.5 hr	565.5 hr
DUT 3	186.1 hr	620.0 hr
DUT 4	510.1 hr	883.8 hr
DUT 5	572.6 hr	
F(t)=50%	143.4 hr	603.9 hr

×4



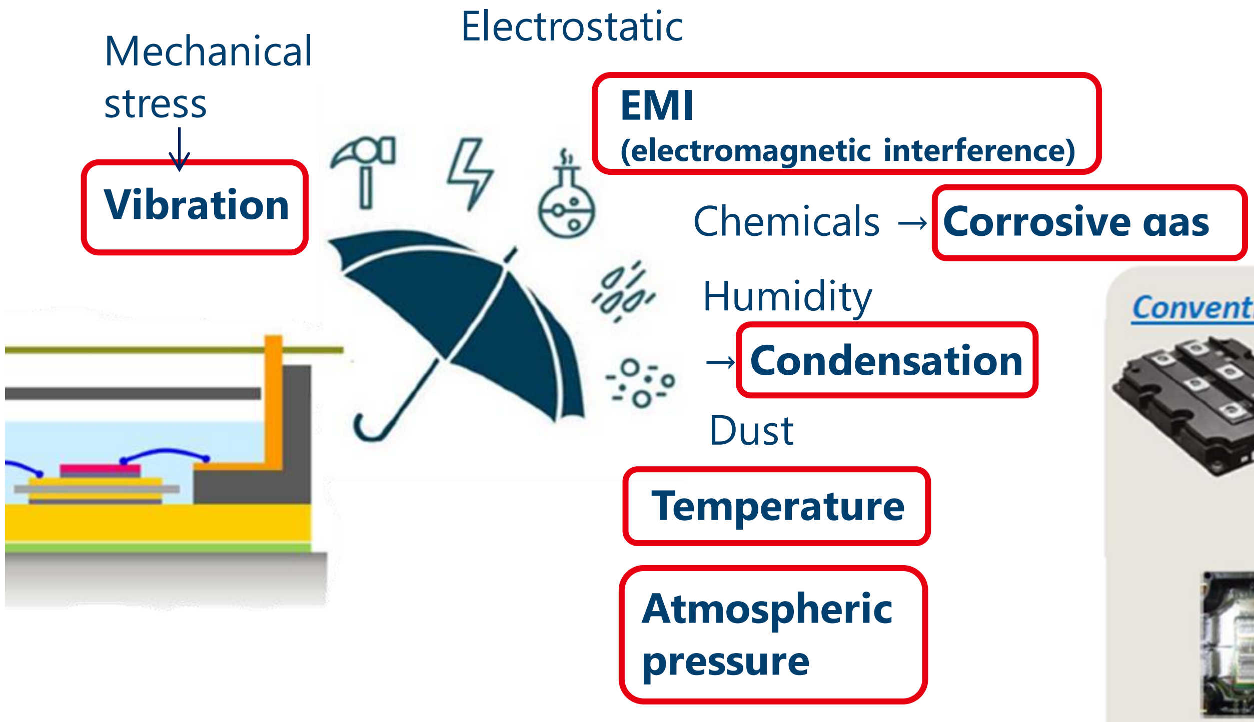
2) Tanaka, N., Ota, K., et al. : "Robust HVIGBT Module Design Against High Humidity", PCIM 2015, May 2015,

05

Challenges

New Package Concept

Challenges – *New Demands*



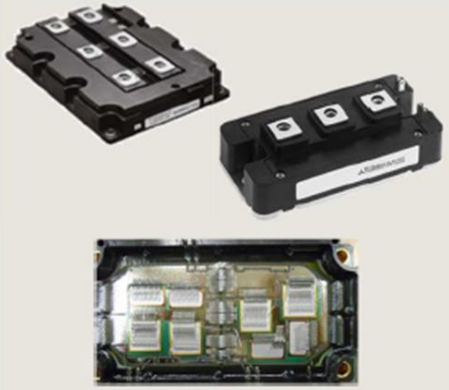
Demand for environmental robustness are becoming **more severe** and **more varied**

Package

Highly protective materials
Additional protection
Highly robust structure

➡ **Resin encapsulation**

Conventional package (case)



Material : silicone gel
Process : pouring

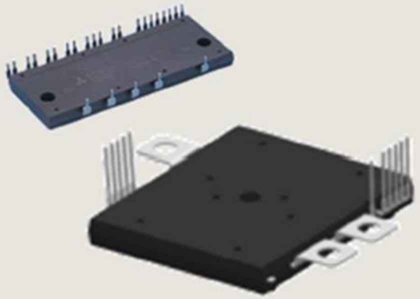
✓ Design flexibility
✓ Capability for larger package

SLC (Solid Cover)

Material : epoxy resin
Process : pouring

✓ Design flexibility
various lay-out, rating current, voltage, topologies
✓ High reliability

Transfer mold package



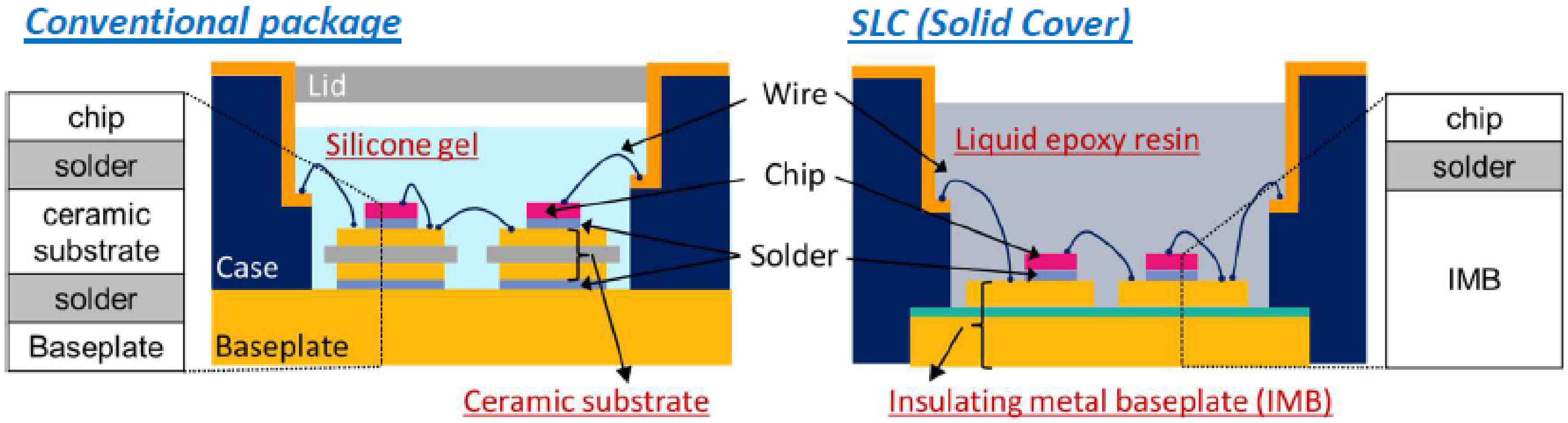
Material : epoxy resin
Process : transfer molding

✓ Suitable for smaller package
✓ High productivity
✓ High reliability

combines the best of both

Challenges – *New Package Concept; SLC*

1. Structure



IMB *(Insulated Metal Baseplate)*

✓ **single substrate** → Reduce the internal inductance
→ Reduce the package size

✓ **Thick copper pattern** → Reduce the thermal resistance
→ Increase chip mounting area

✓ **eliminate the solder layer** → Increase the thermal cycle capability
→ Reduce the thermal resistance

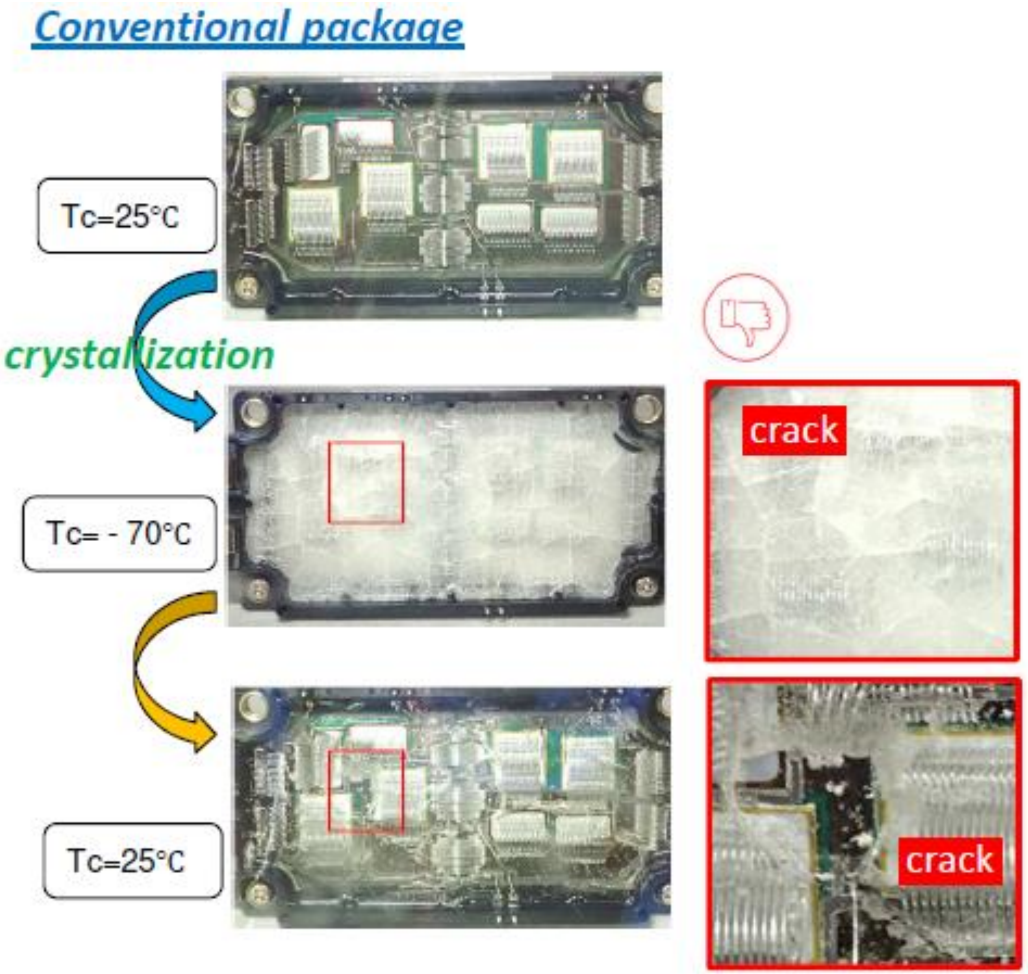
Resin encapsulation

✓ **Robustness** → Vibration proof, Low air pressure proof, Corrosive gas proof

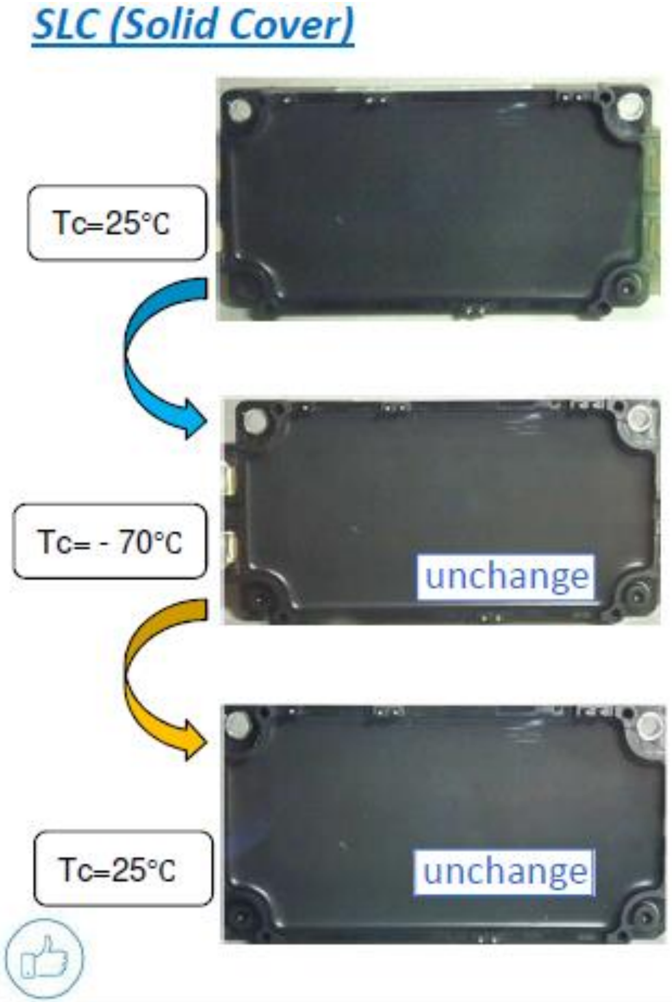
5) Kaji, Y., Hatanaka, Y., et al. : "Novel IGBT Modules with Epoxy Resin Encapsulation and Insulating Metal Base Plate", Proc. ISPSD 2016,
6) Asada, S., Kaji, Y., et al : "Resin Encapsulation Combined with Insulated Metal Baseplate for Improving Power Module Reliability, PCIM 2016,

Challenges – *New Package Concept; SLC*

2. Low temperature stability



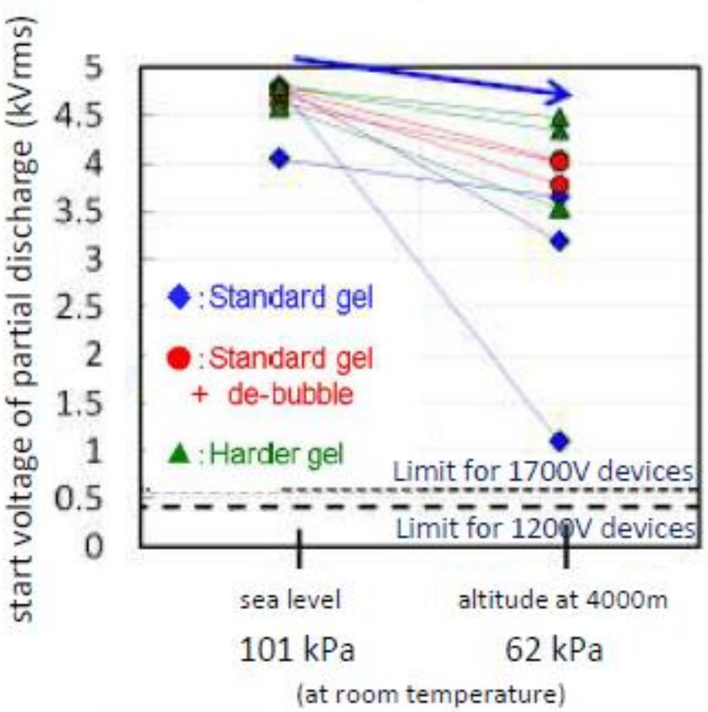
Silicone gels crystalize around -40°C
✓ Irreparable crack are induced



Epoxy resin has "no" crystallization temp.
✓ Stable under low temperature

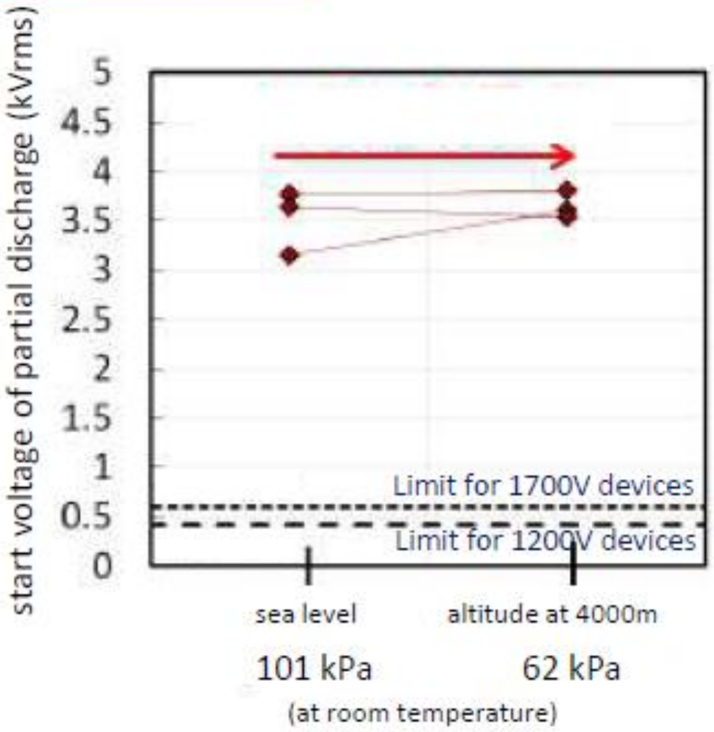
3. Low pressure stability

Conventional package



Silicone gel : "flexible"
- ✓ Bubbles easily generate and move
- ✓ Affected by atmospheric pressure

SLC (Solid Cover)



Epoxy resin : "hard"
- ✓ No bubble generation and movement
- ✓ Not affected by atmospheric pressure

4. Robustness against corrosive gases

Conventional package

With gel potting

Insulation layer surface

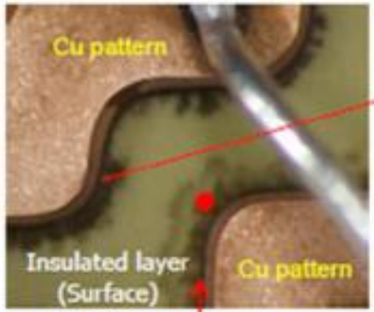


Fig 8

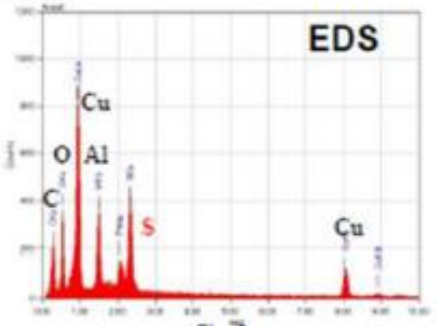


Fig 9

Sulfur was detected

Dendrites (compound of Cu and S)

SLC (Solid Cover)

With DP-resin potting

Point A. Insulation layer surface

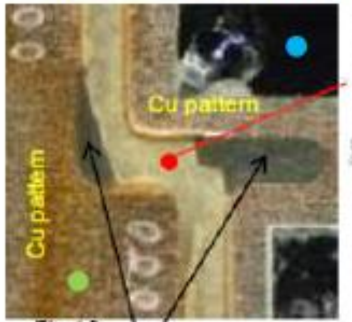


Fig 10

Gray part is remained DP-resin, not dendrite.

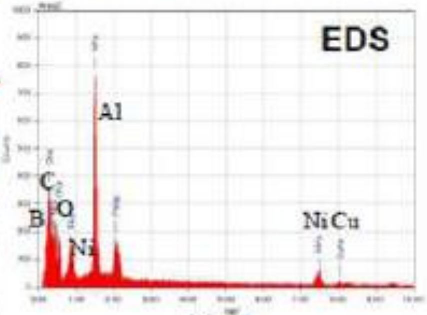
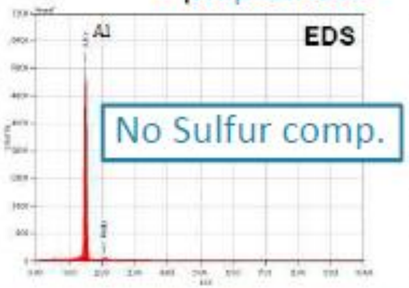


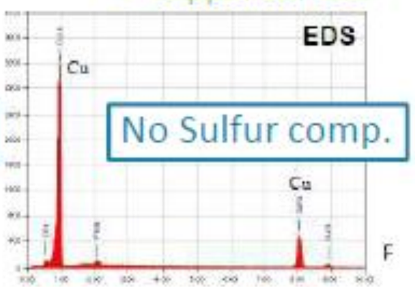
Fig 11

No Sulfur components

● chip surface



● copper surface



Epoxy resin : Low Gas-permeable
✓ Protect from corrosive gas

06

Summary

SUMMARY

01 The expanding use of power modules has led to demands for robustness against harsher environments.

02 The impact of humidity is particularly important and highlighted.

03 We focused on the edge-terminated area of the power chip and identified new failure mechanism and lifetime model.

04 High robustness against humidity is achieved with advanced chip design and packaging.

05 Development of resin encapsulated structures for harsher and more diverse environmentals demands.

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