The application of SiC on vehicles and its future

4th July, 2018

Dr. Kimimori Hamada
Project General Manager
EHV Electronics Design Div.
Toyota Motor Corporation

Contents

What our customers and society require for cars

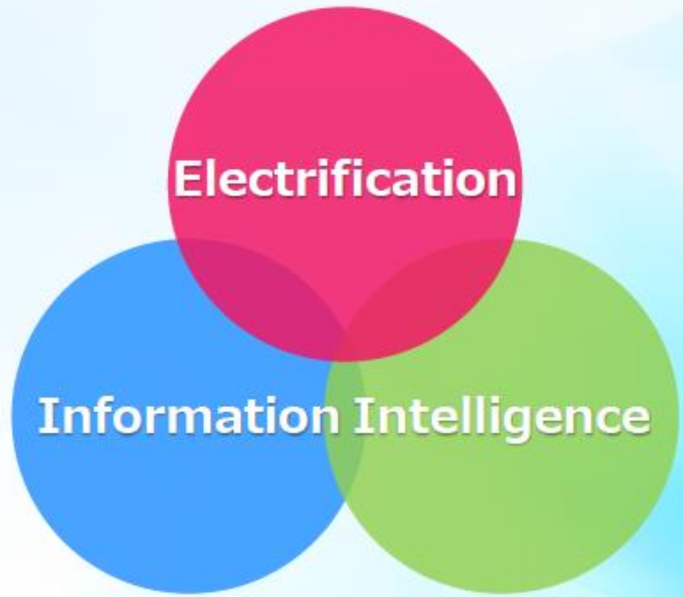
Cars facing profound transformation that comes only once in 100 years

=

Provide new value and grasp chance for business expansion

Ever-better cars
(Beloved cars)

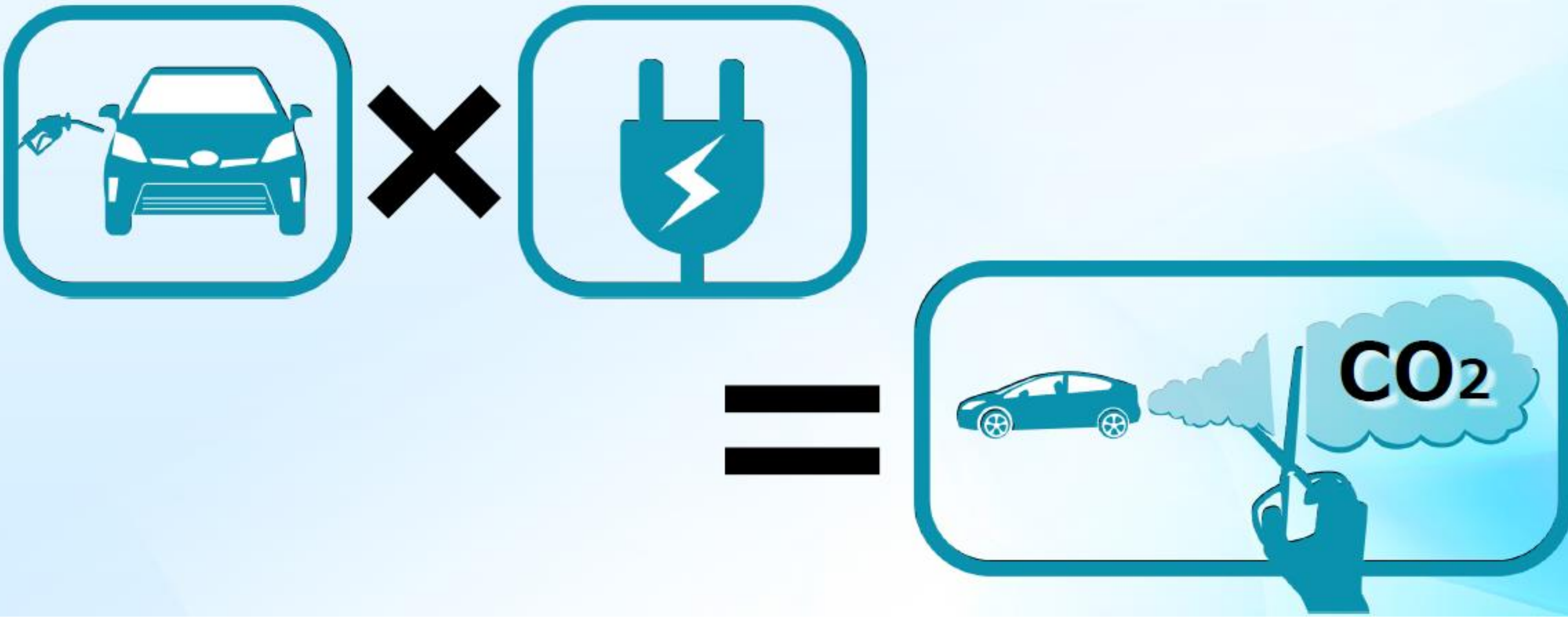
+



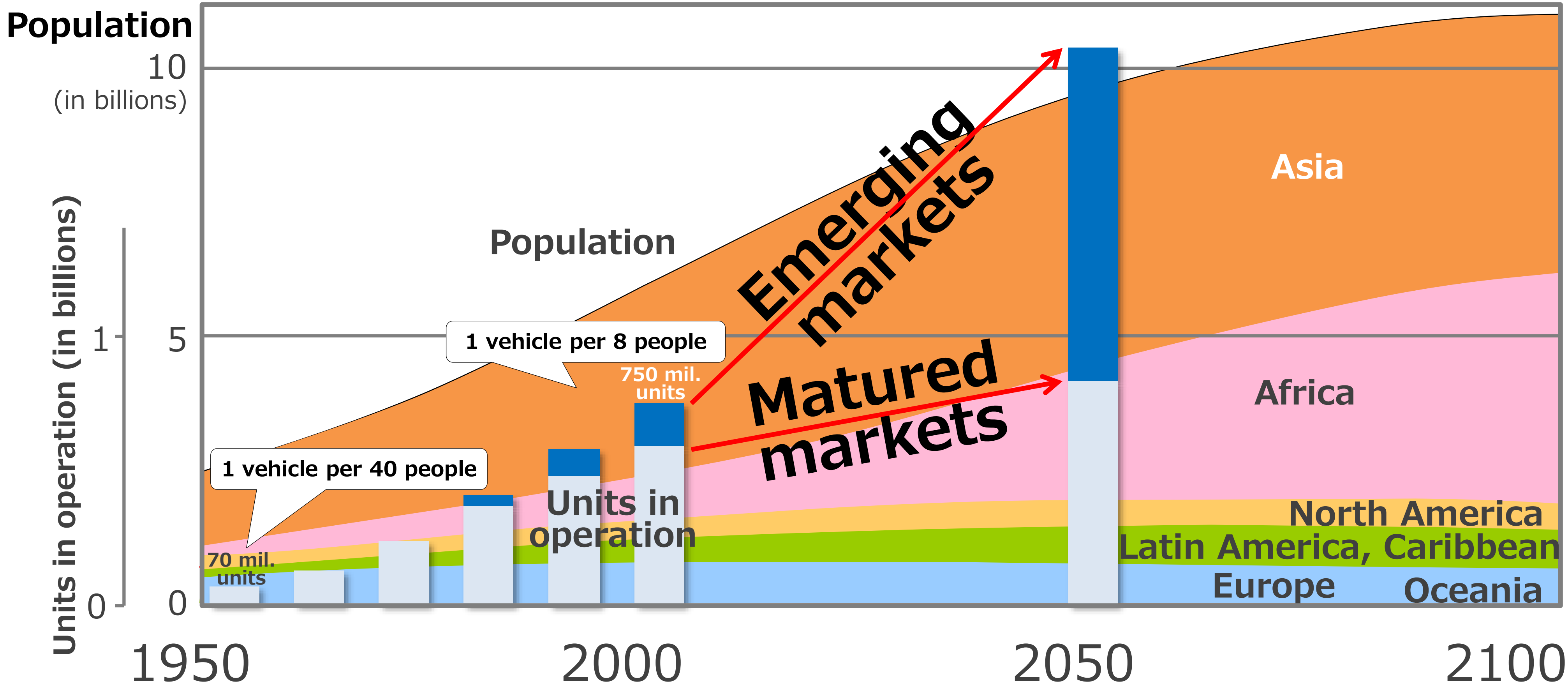
Strategic shift

To reduce CO_2 emissions･･･

Vehicle electrification is essential.



Global Population Growth and Vehicle Units in Operation



Population and number of vehicles on load will grow mainly in emerging markets

Sources: 1) United Nations Department of Economic and Social Affairs
2) World Business Council for Sustainable Development

Toyota's Basic Response

To address 3 issues,
vehicle electrification is essential

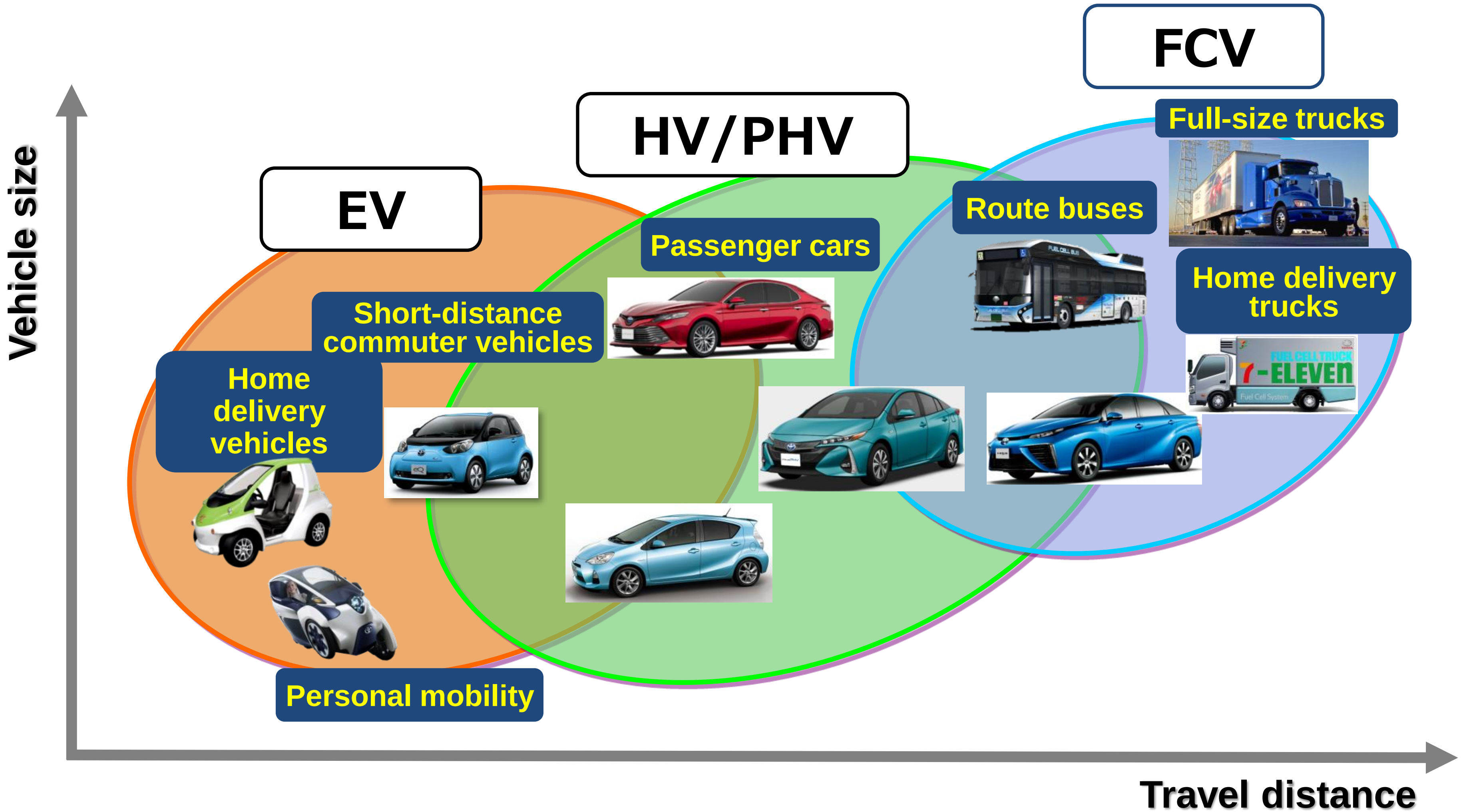
1) **Improving fuel efficiency**
2) **Reducing CO_2 to prevent global warming**
3) **Making emissions cleaner to prevent air pollution**

Environment-friendly vehicles contribute to the environment only when widely used.

Contents

Toyota's development of electrified vehicles

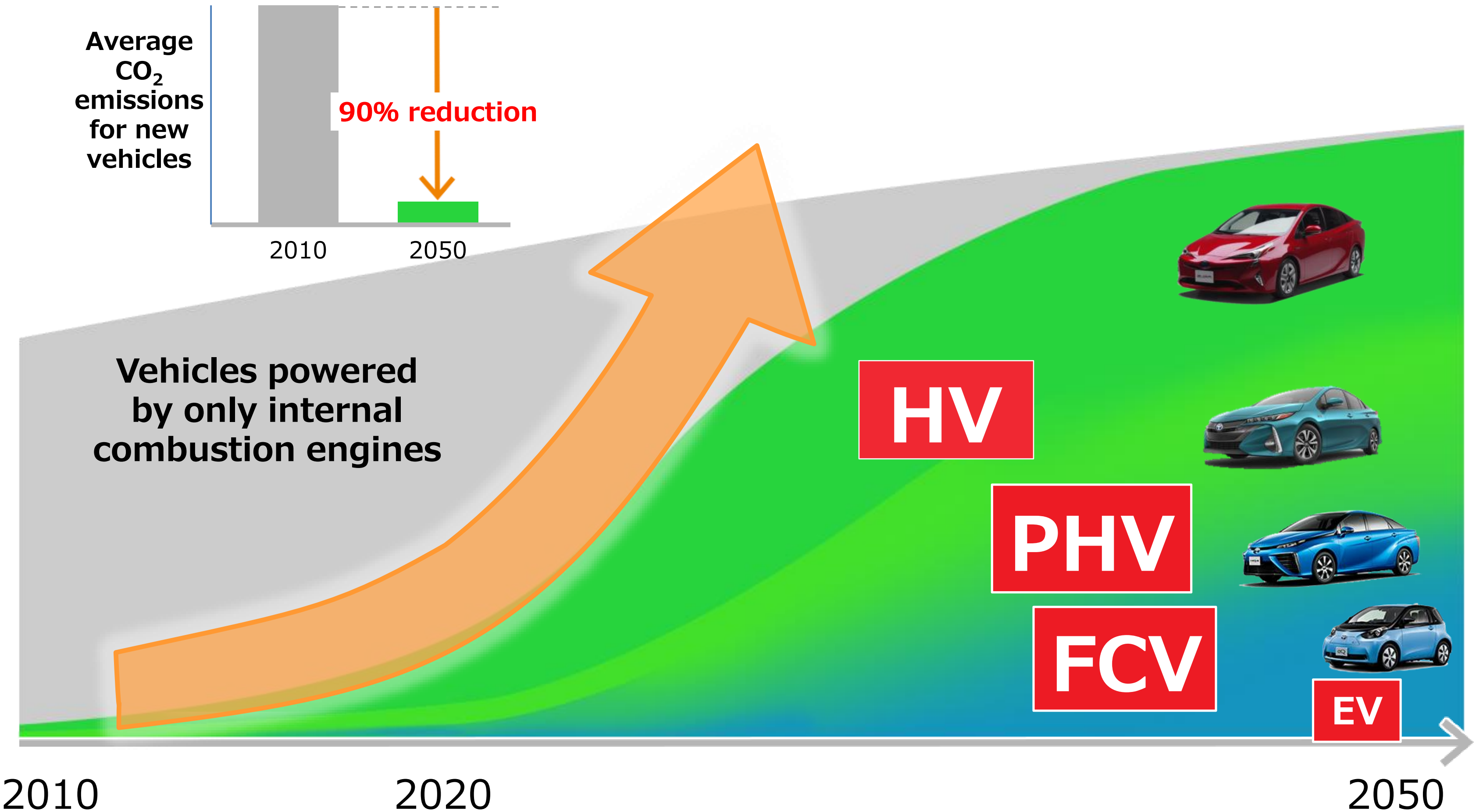
Environmentally friendly electrified vehicles



EVs: Short-to-medium distance; HVs & PHVs: Wide-use; FCVs: Medium-to-long distance

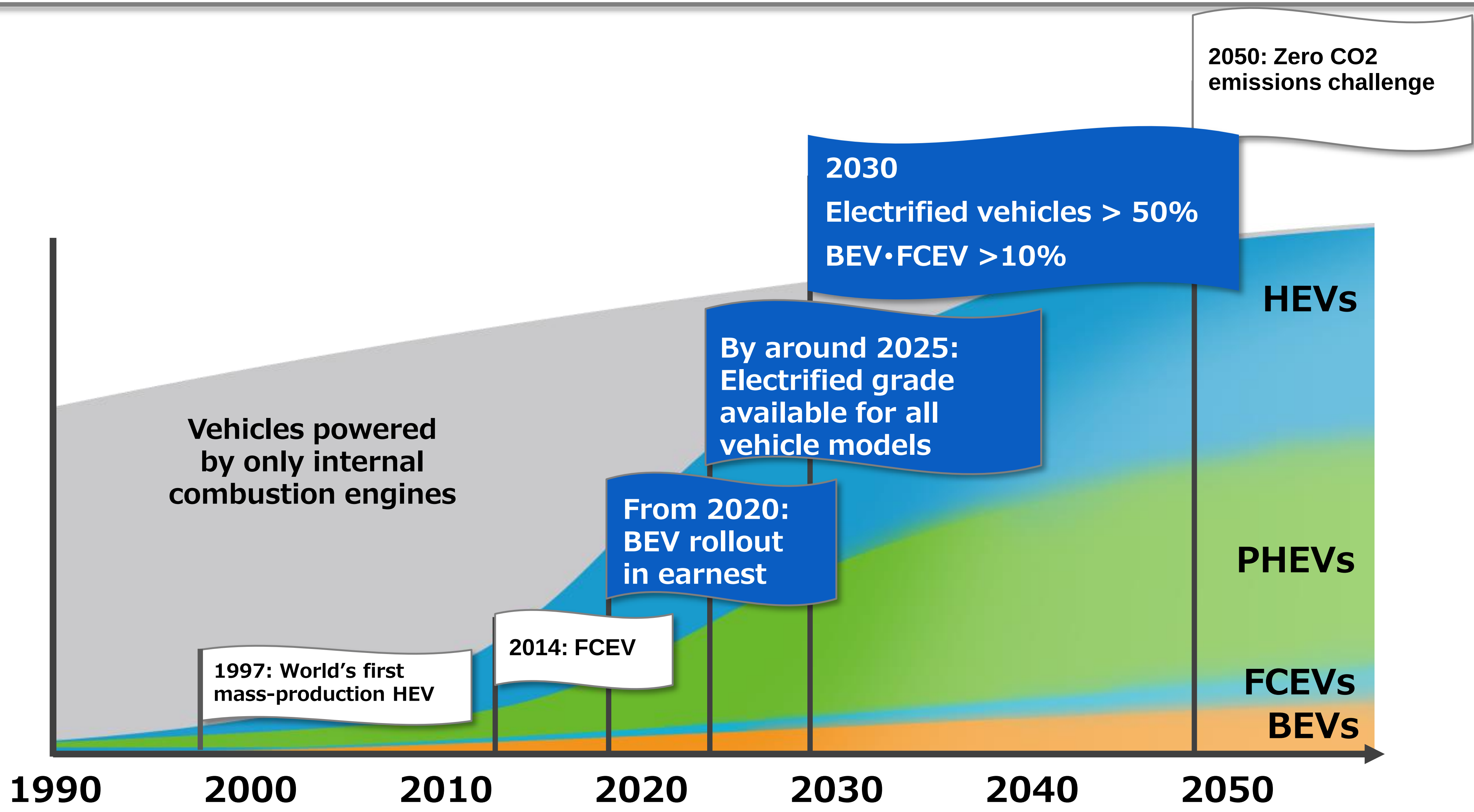
New Vehicle Zero CO_2 Emissions Challenge

Challenge 1: New-vehicle Zero CO_2 Emissions Challenge

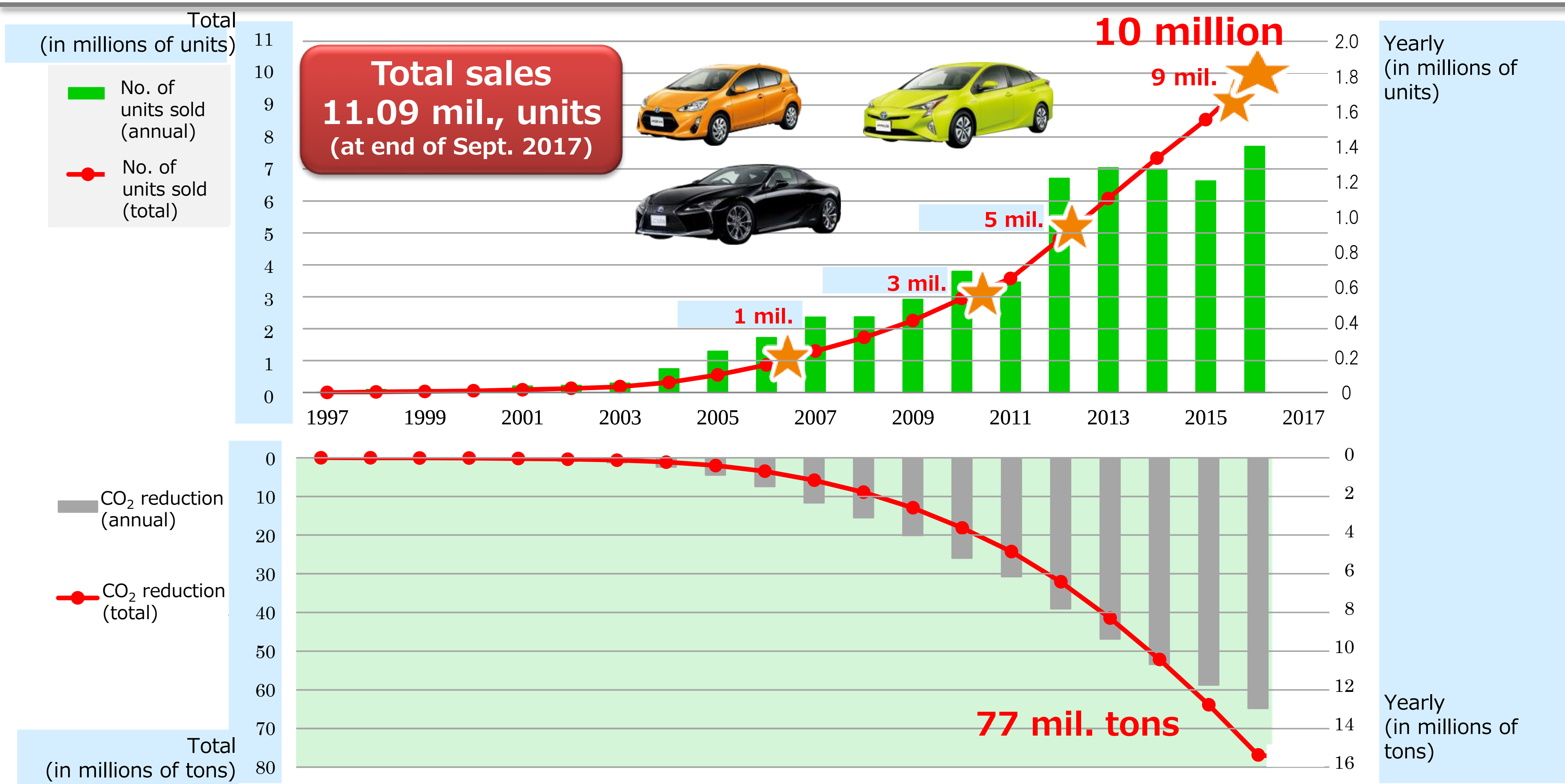


Accelerate next-generation vehicle development toward 90% reduction in CO_2 emissions

Vehicle electrification milestones



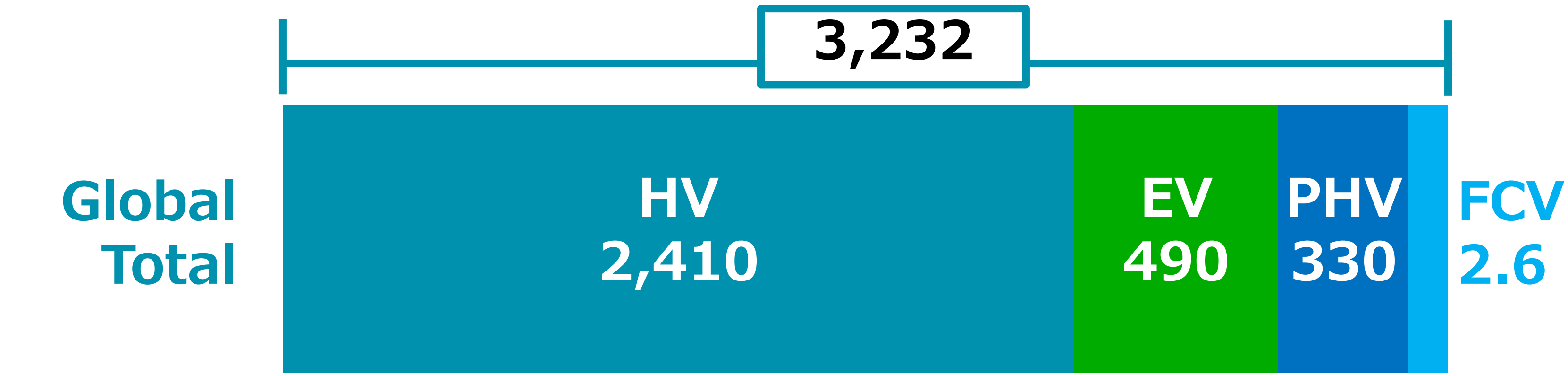
Toyota HV Sales Results & CO_2 Reduction



Total HV sales reached 10 million units in January 2017!

CO_2 reduction compared to similar gasoline-engine vehicles was 77 mil. tons.

Top OEM of Electrified Vehicles



43%

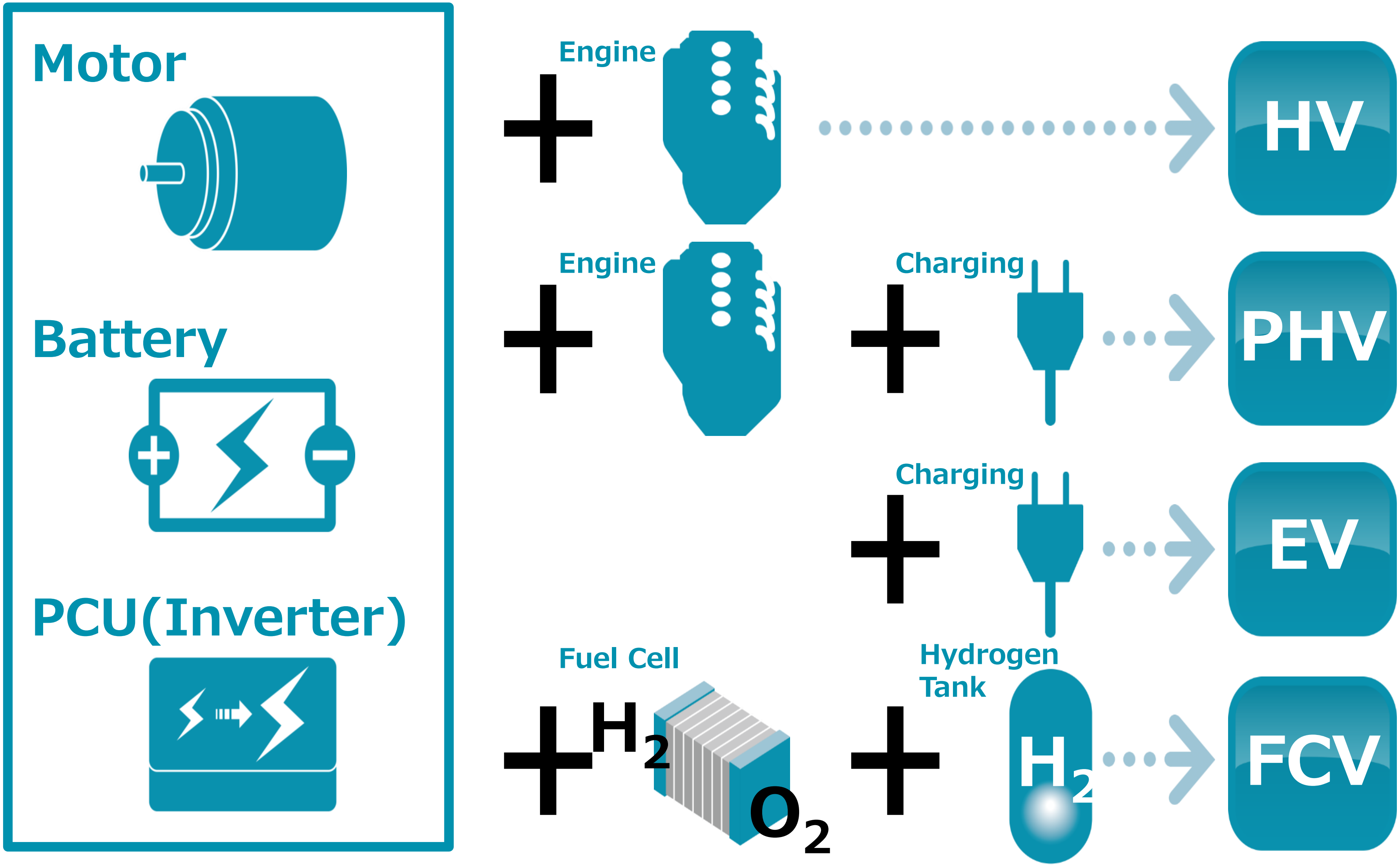
Electrified Vehicle Market Share (CY 2016)

(Unit: 1,000 vehicles)
Calculated by Toyota from IHS data

Contents

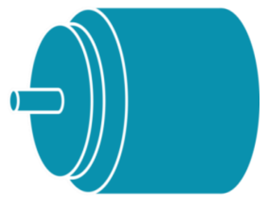
Toyota's vehicle electrification technologies

3 Core Technologies and Electrified Vehicles



Evolution of 3 Core Technologies

Motor

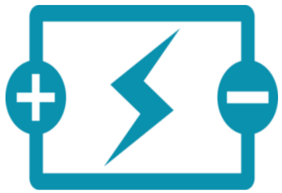


Output : 200% UP

Volume : 50% DOWN

Power Density 400% UP

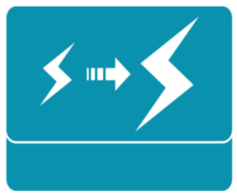
Battery



Weight : 30～50% DOWN

Volume : 60% DOWN

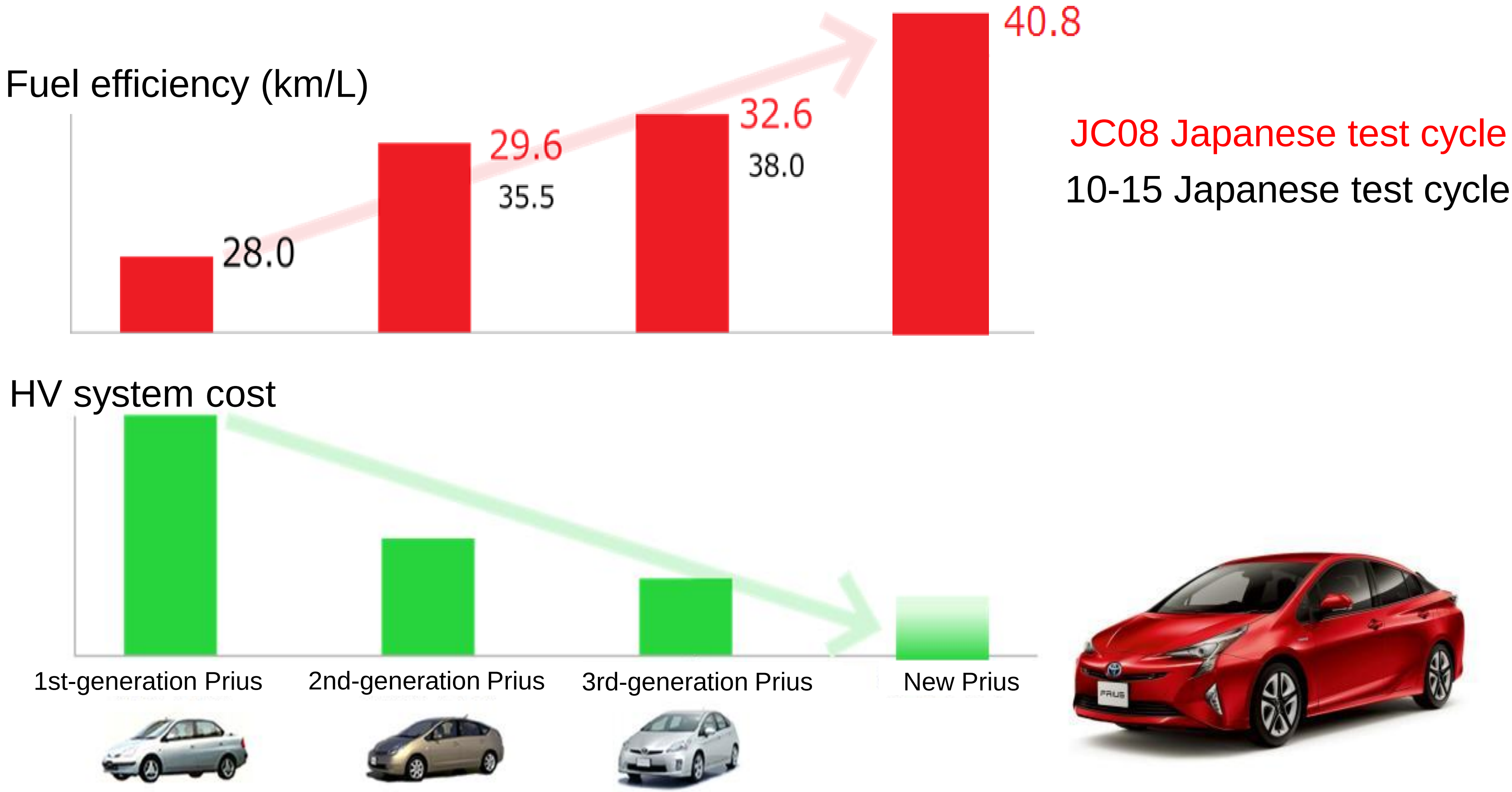
PCU



Energy loss : 80% DOWN

Volume : 50% DOWN

Higher Fuel Efficiency & Lower Hybrid System Costs



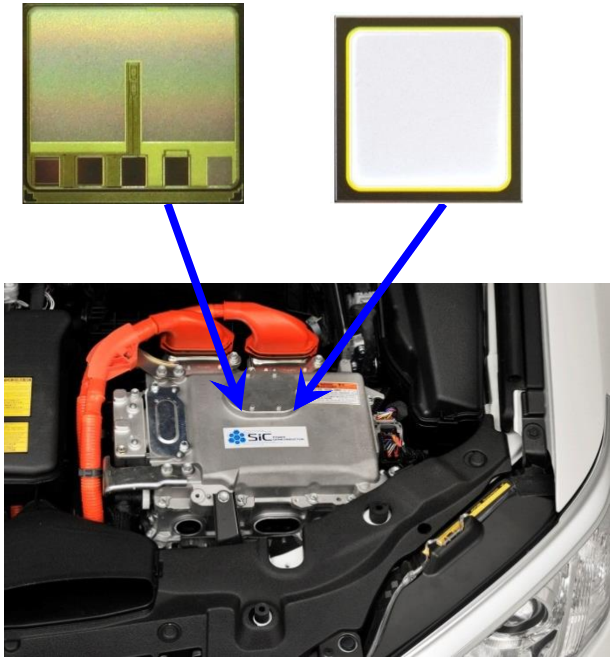
HV technology significantly evolved in terms of fuel efficiency with reduced cost

Contents

Application of SiC Power Semiconductor Devices on Electrified Vehicles

CAMRY

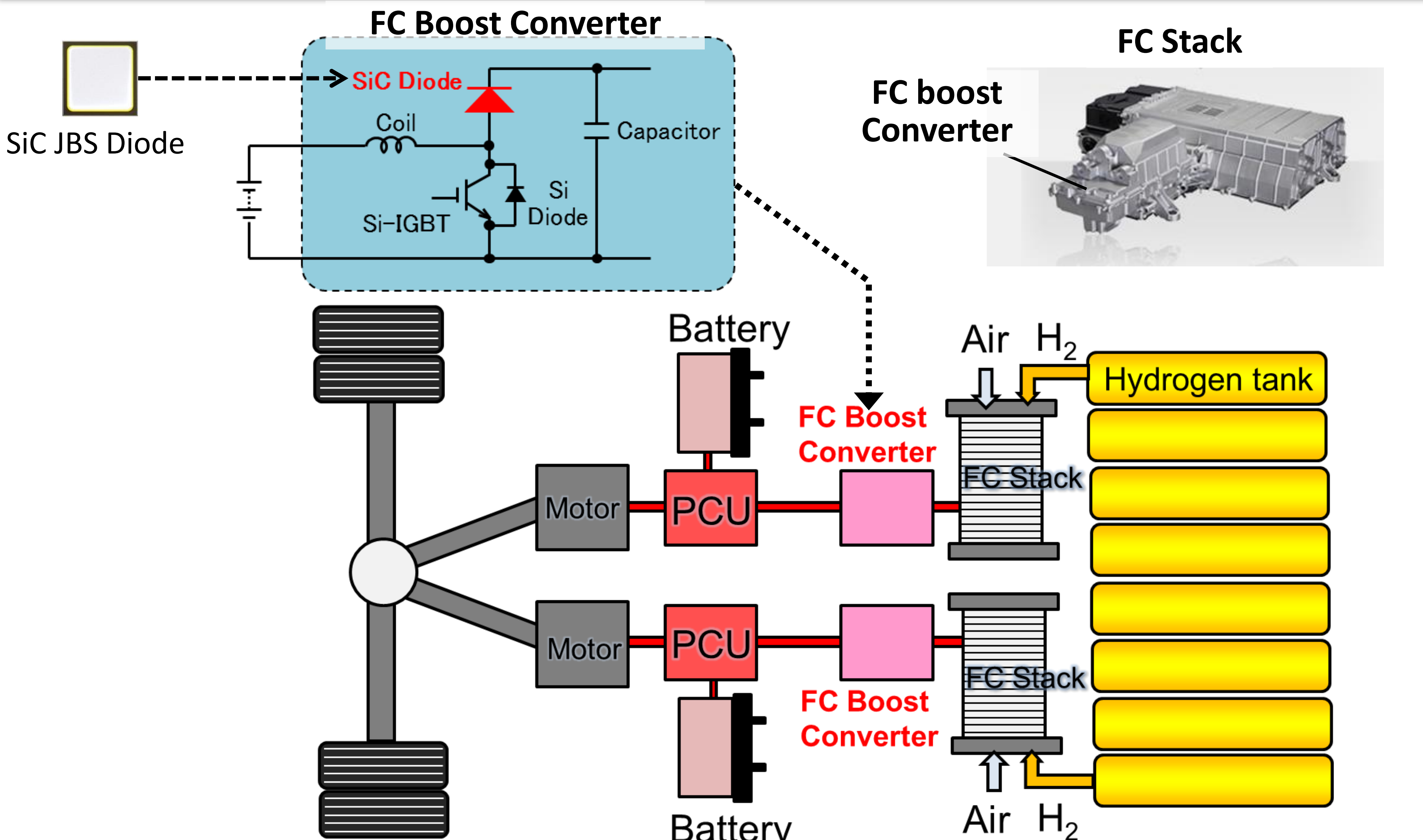
SiC MOSFET SiC JBS Diode



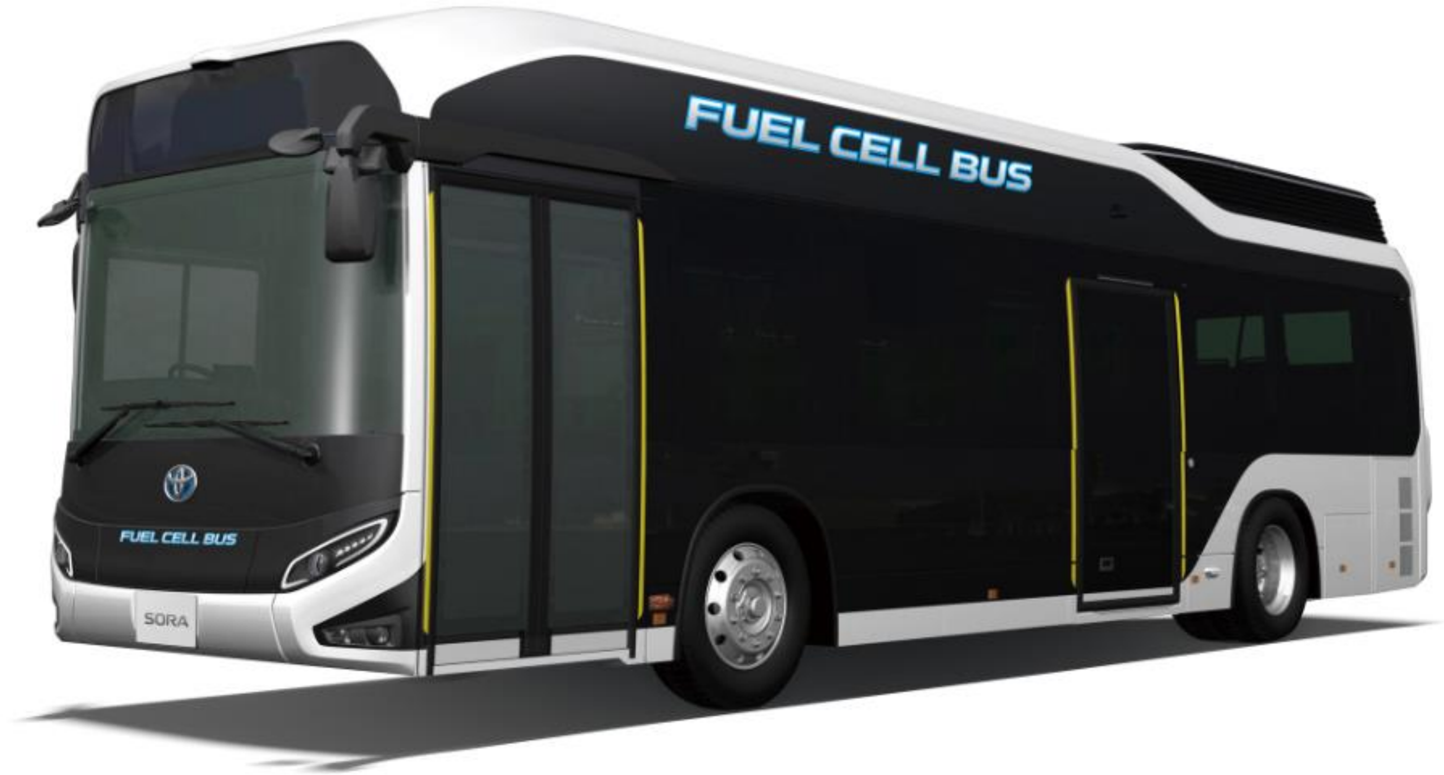
Full SiC PCU

- Installing SiC power semiconductors (MOSs and diodes) in the PCU
- We started road testing of this Camry in early February, 2015
- Evaluating fuel efficiency under various driving condition

Fuel cell system of the FC bus



Tokyo Toei FC Bus



To(都)05line: Tokyo station Marunouchi-Minamiguchi～Tokyo Big Sight

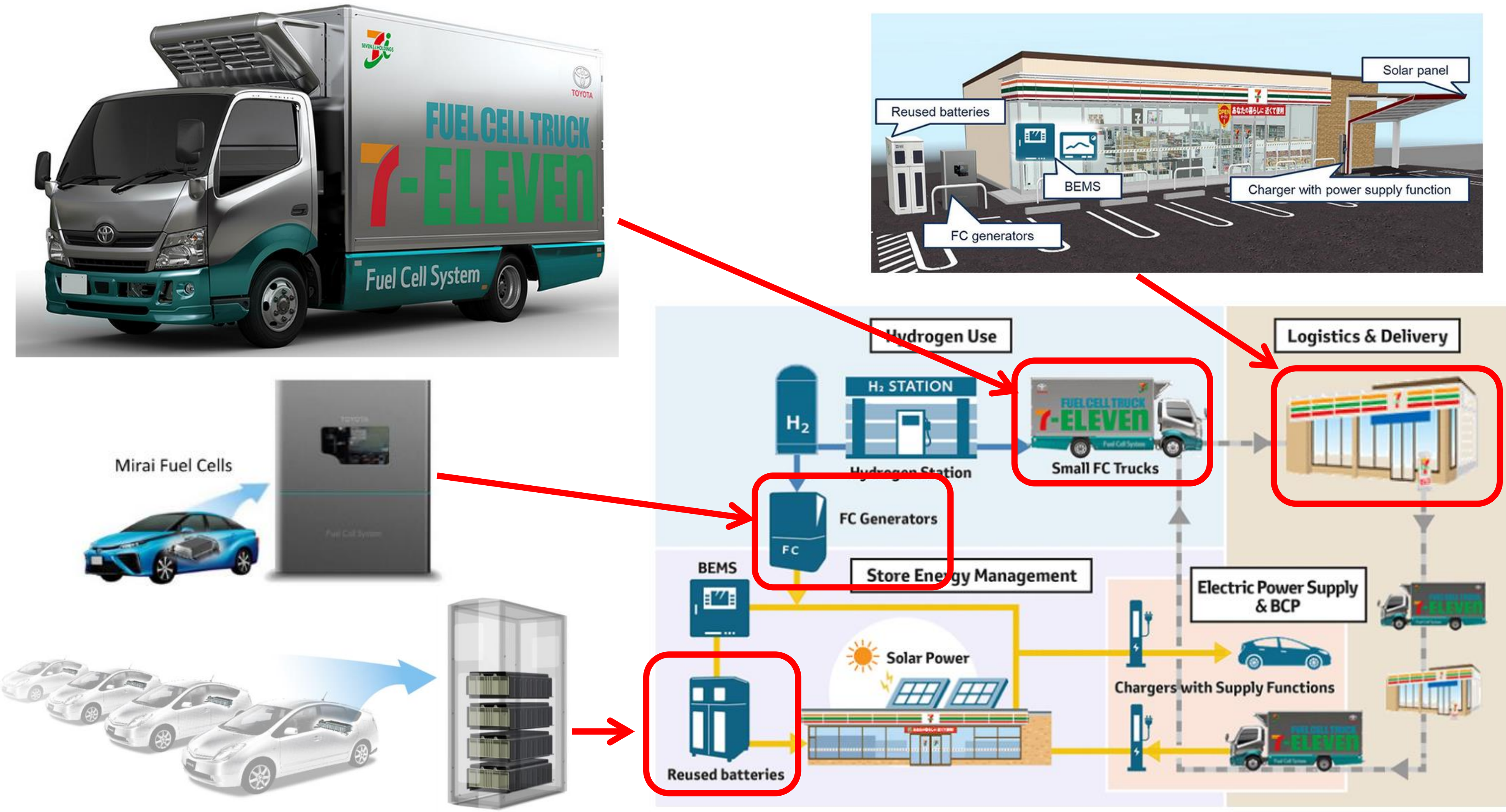
- Regular commercial operation in Tokyo since March, 2017
- **Over 100 FC Buses will be introduced before Tokyo Olympic/Paralympic games**

Heavy-duty FC Track

The Project Portal heavy-duty truck concept generates more than 670 horsepower and 1,325 pound feet of torque from two Mirai fuel cell stacks, and its estimated driving range is more than 200 miles

Toyota Drives the Future of Zero Emission Trucking

Next generation Convenience Stores and Small FC Truck



Toyota Promotes CO2 Emission Reduction and Energy Conservation in Convenience Store Distribution and Operation

Electric Vehicles

Toyota to Introduce 10 New Electrified Vehicles in China by 2020

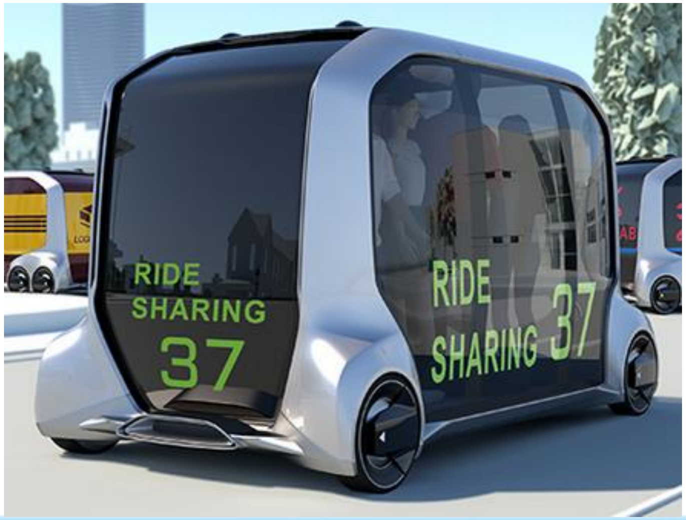
Corolla PHEV version

Levin PHEV version

C-HR and IZOA (Internal combustion engine version)

City Commuters

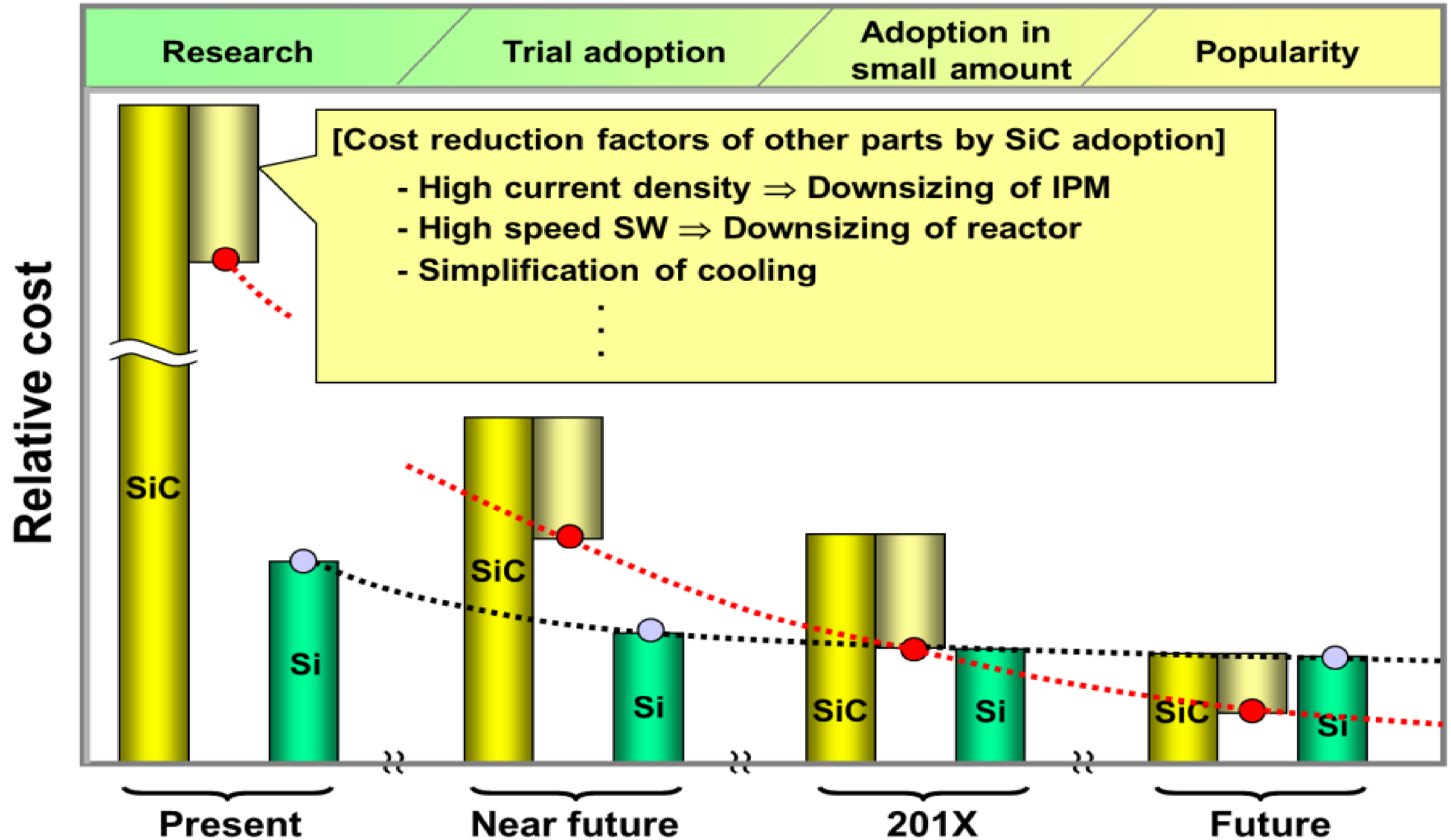
E-Palette Concept



Toyota Strongly Promotes the Development of Electric Vehicles.

Contents

Scenario of Successful SiC



ICSCRM2007(Ohtsu) Keynote Speech

Challenges to reduce cost:
1) Development of Low $R_{on}Q_{gd}$ MOSFET 2) Practical use of body diode of MOSFET

Contents

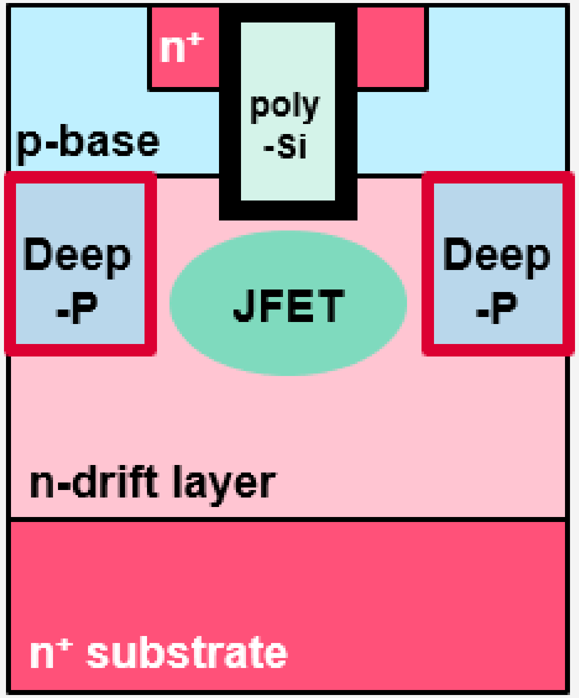
Development of Trench MOSFET With Ultra Low $R_{on}Q_{gd}$

Deep-P Encapsulated 4H-SiC Trench MOSFETs With Ultra Low $R_{on}Q_{gd}$
(DENSO@ISPSD2018)

Development of ultra low $R_{on}Q_{gd}$ power MOSFET

SiC trench MOSFETs developed in DENSO

Schematic View [1]

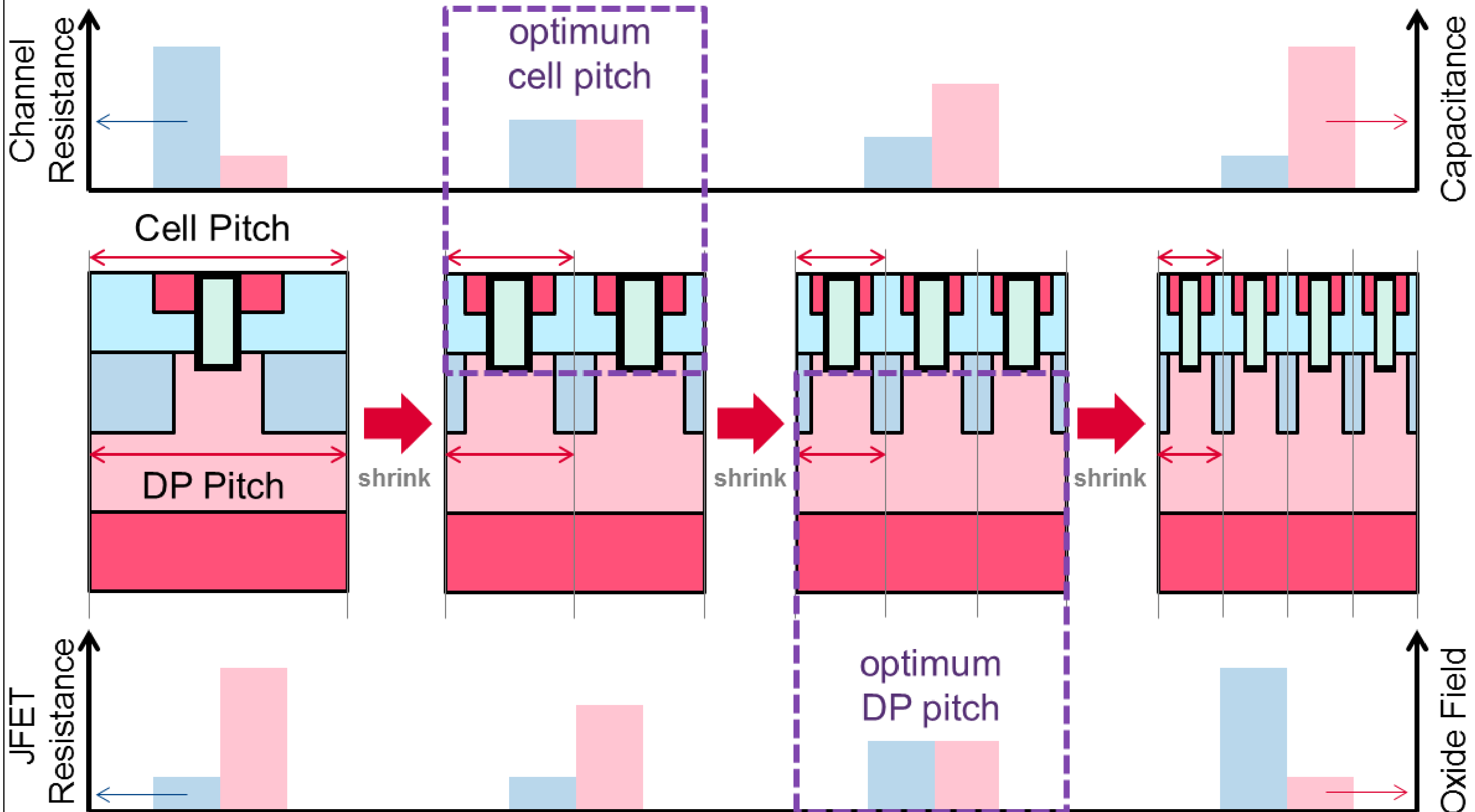


Deep-p region protects gate oxide at off-state
Deep-p region forms JFET resistance at on-state

[1] DENSO REVOSIC HP https://www.denso.com/jp/ja/products-and-services/industrial-products/sic/

Development of ultra low $R_{on}Q_{gd}$ power MOSFET

Issues of pitch shrinking



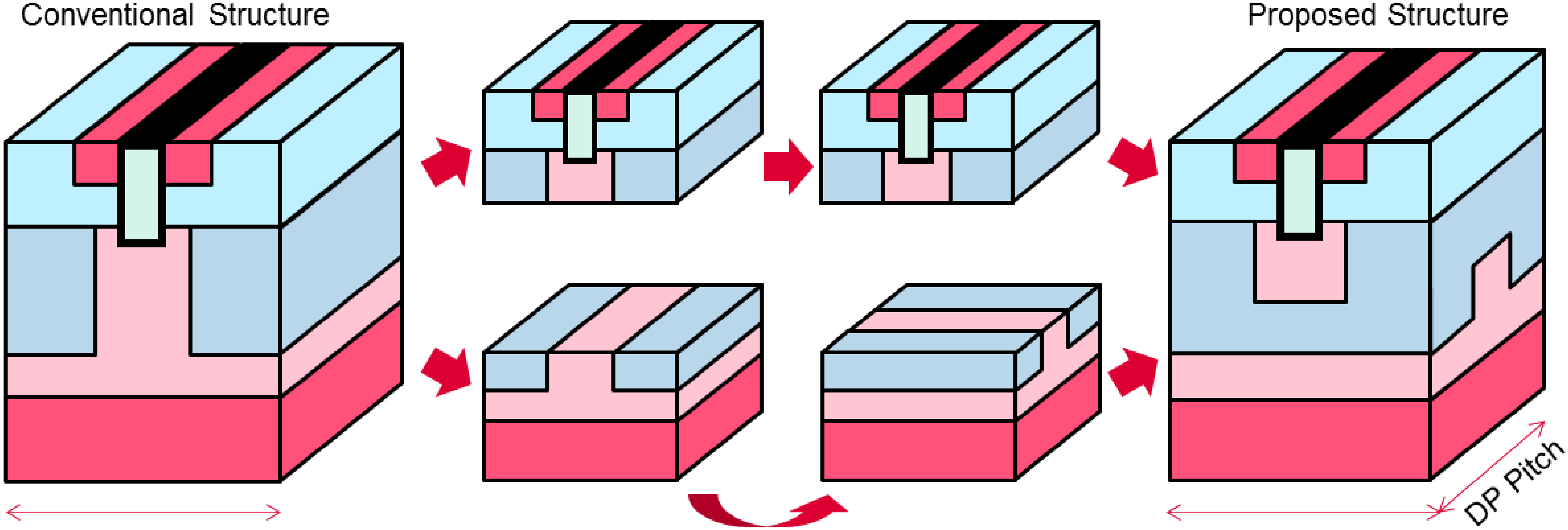
optimum cell pitch ≠ optimum DP pitch

➡ Flexible pitch design is required

Development of ultra low $R_{on}Q_{gd}$ power MOSFET

Device concept

Our Approach: Rotation of DP region to enhance flexibility of pitch design[2]



Merit: low R_{ch}, low R_{JFET}, low E_{OX}, low C_{gd}

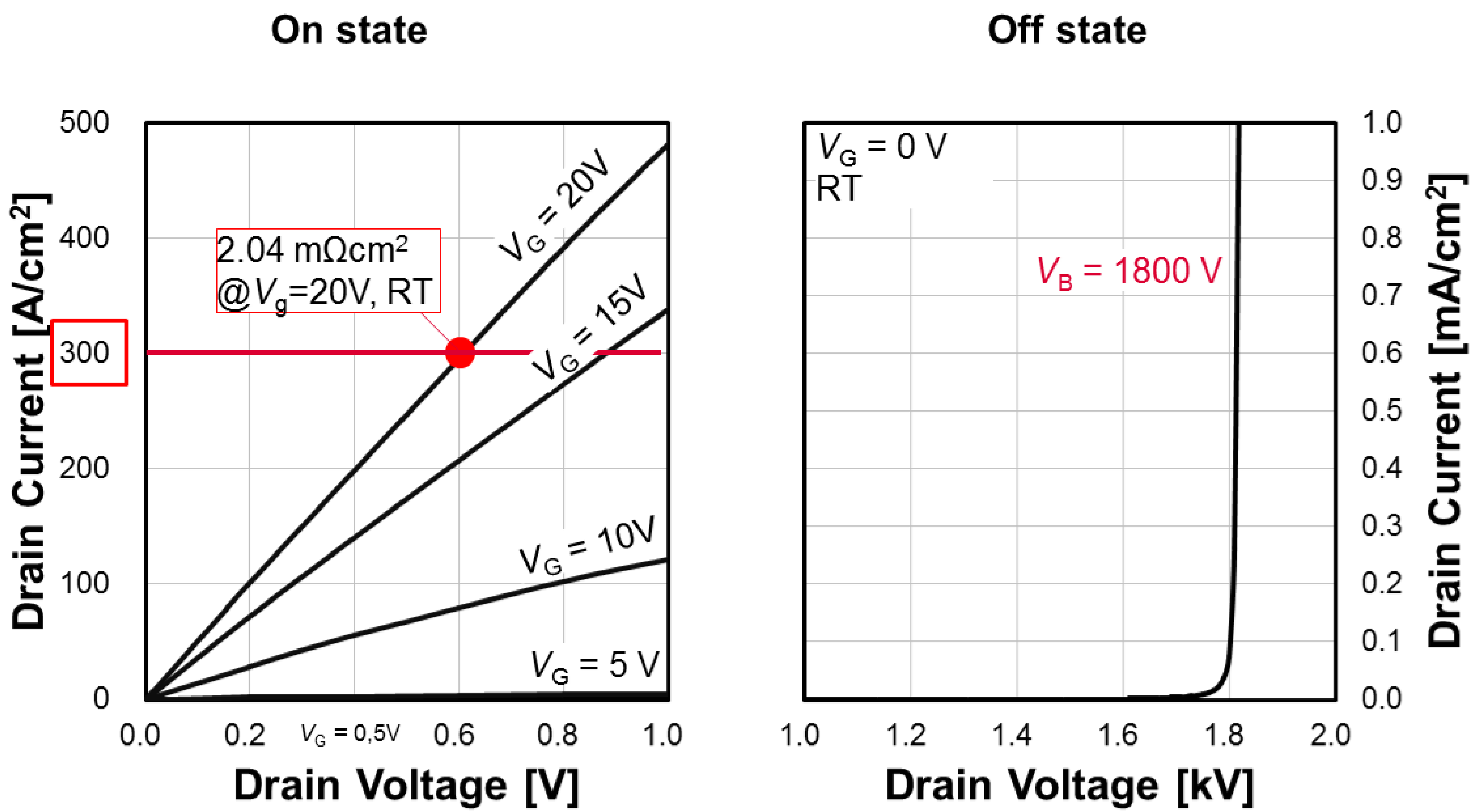
next slide

Independent pitch design improves device performance

[2] A. Ichimura et al, "4H-SiC Trench MOSFET with Ultra-Low On-Resistance by using Miniaturization Technology", ICSCRM2017

Development of ultra low $R_{on}Q_{gd}$ power MOSFET

Static characteristics of higher voltage type

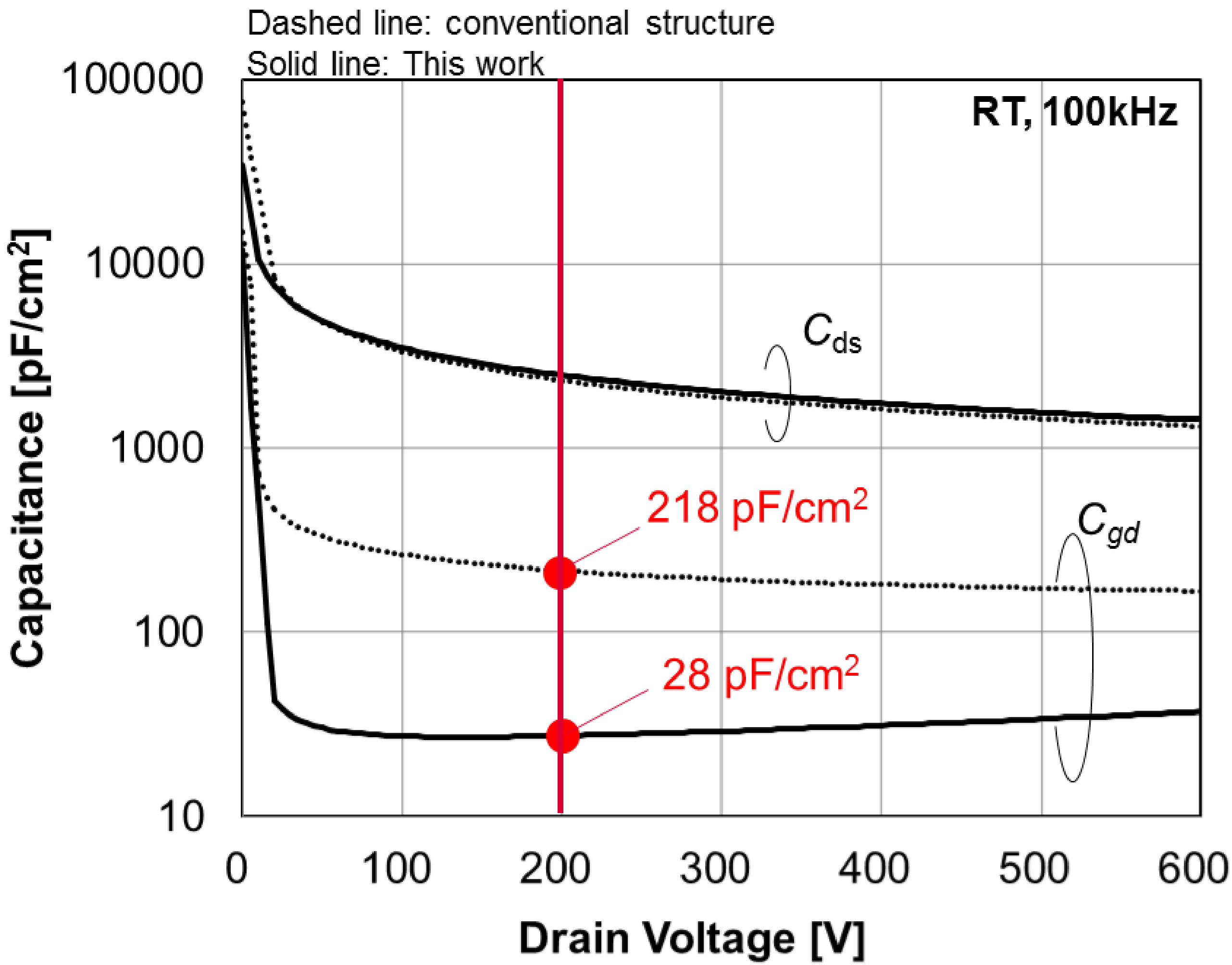


V_{th}: 2.7V @V_d=10V, I_d=100mA/cm², RT

BV of 1800V and $R_{on}A$ of 2mΩcm² are achieved

Development of ultra low $R_{on}Q_{gd}$ power MOSFET

Static characteristics of higher voltage type



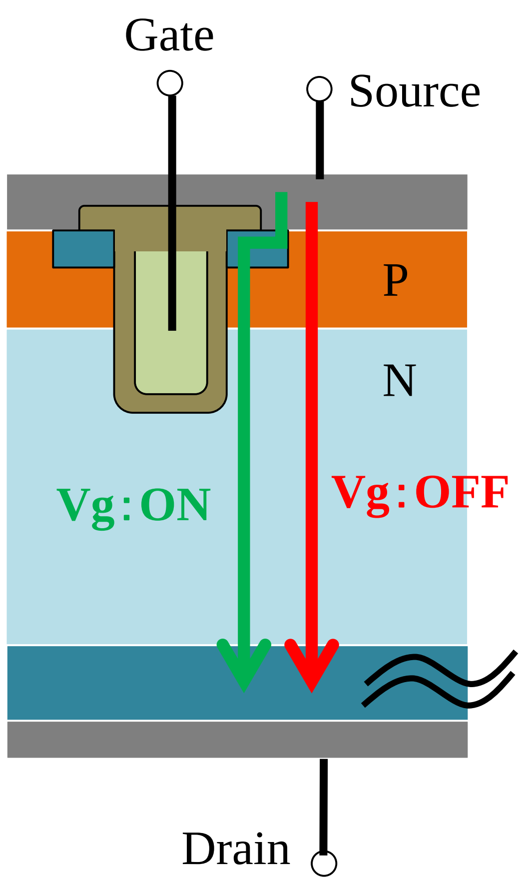
C_{gd} is successfully reduced by 87%

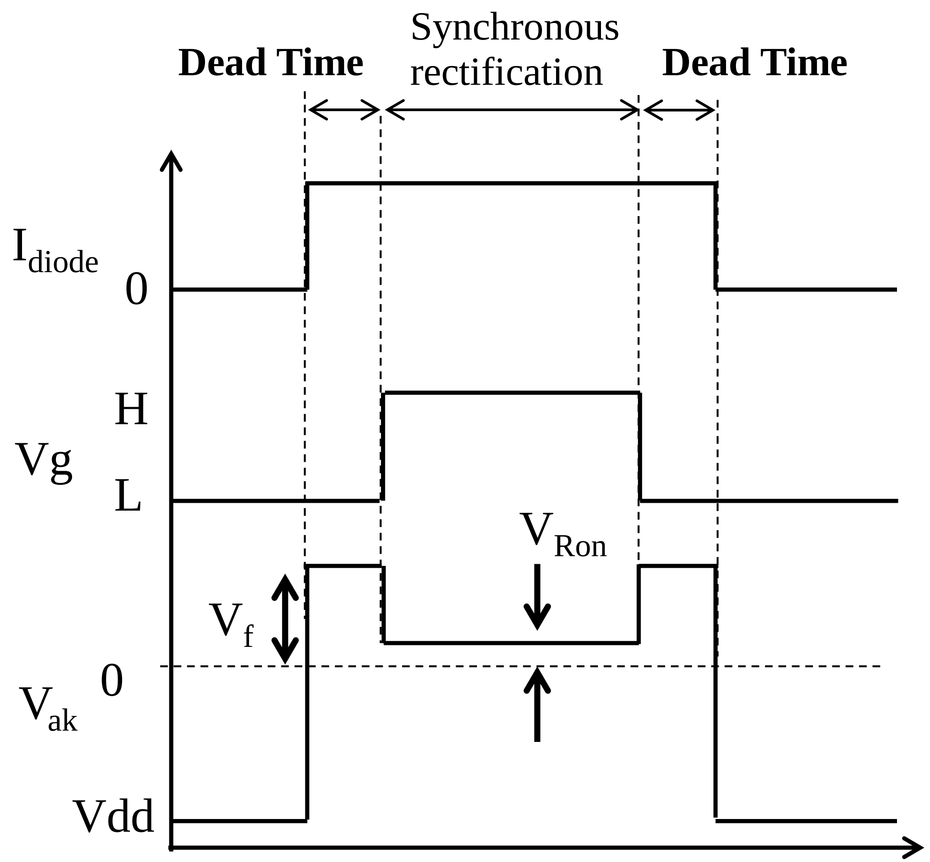
Contents

Stacking Fault Expansion due to Body Diode Operation and the Countermeasures

Synchronous Rectification

- In order to reduce conduction losses and device cost, the synchronous rectification is important technology.
- However, the body diode of MOSFET operates during dead time.



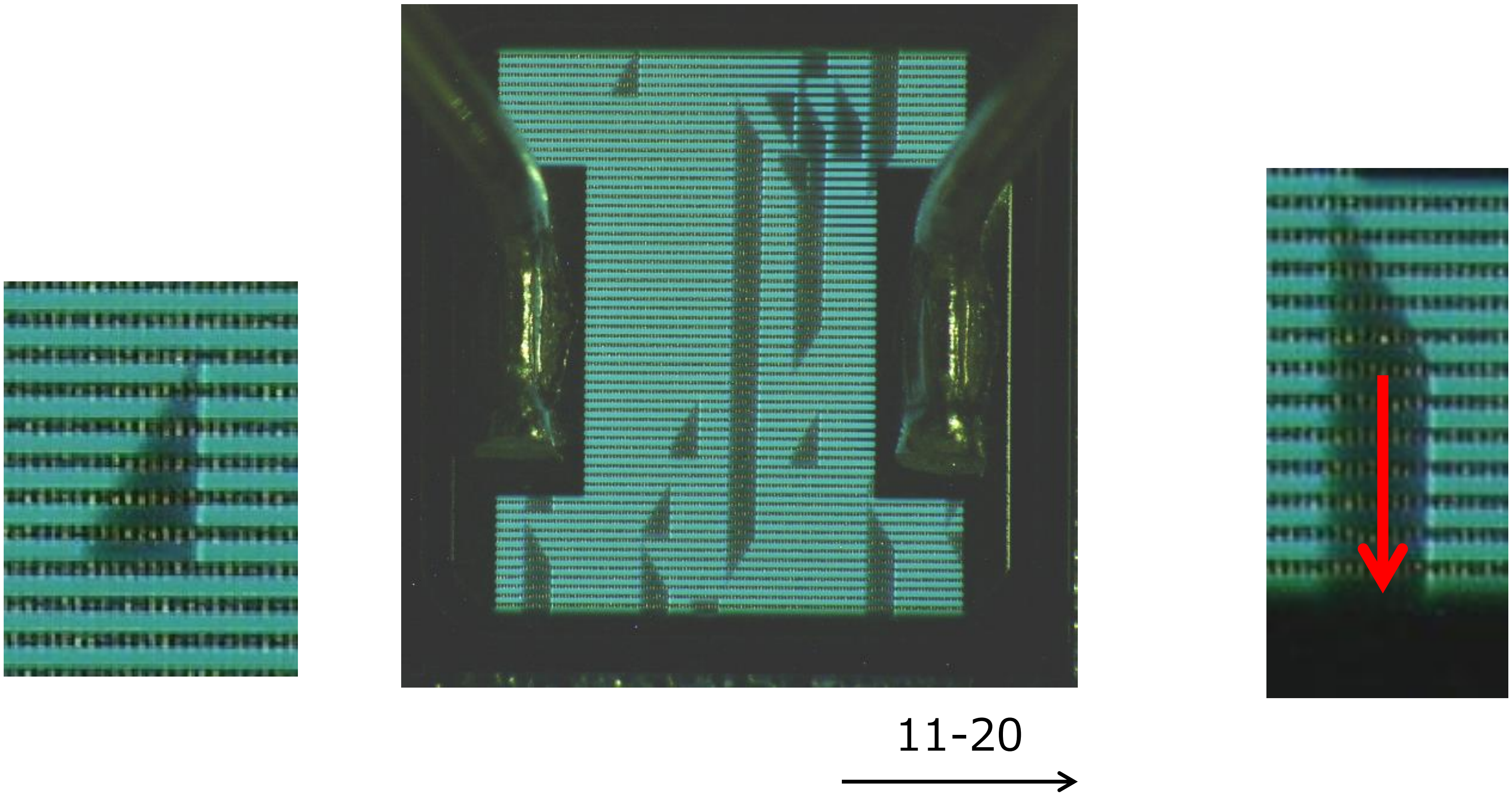


Time chart of synchronous rectifier operation

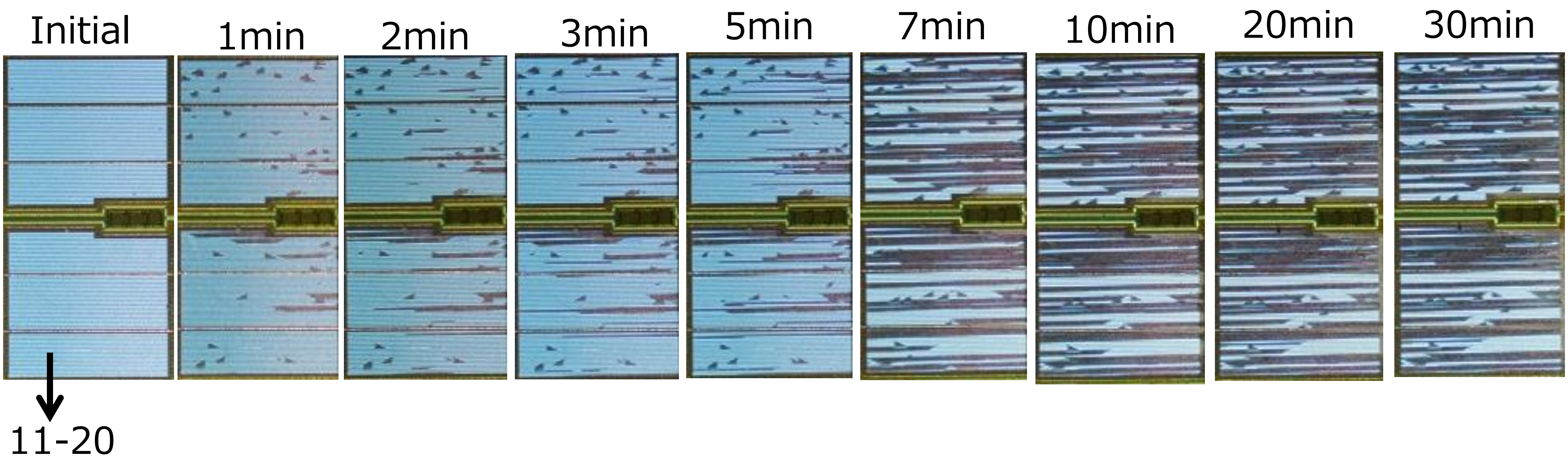
Types of Stacking Faults

- There are Two types of Stacking Faults: Triangle and Bar-shaped.
- The expansion of the triangle SFs ended when the shape reached a triangle.
- Bar-shaped SFs expand continuously to the end of the active area.

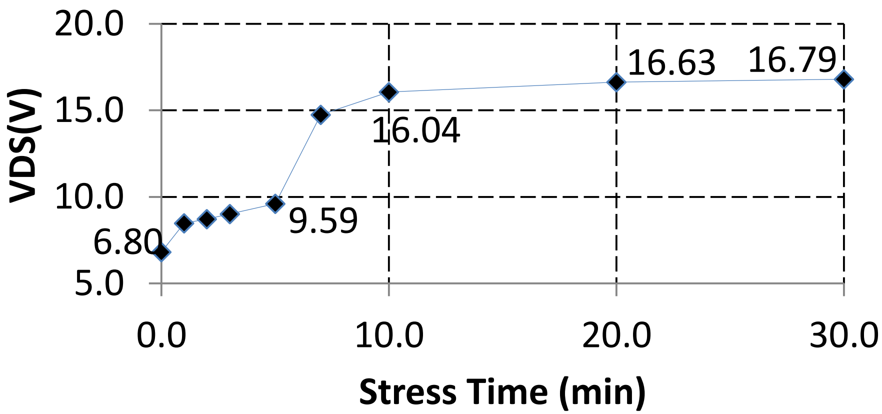
⇒ Larger impact on electrical properties.



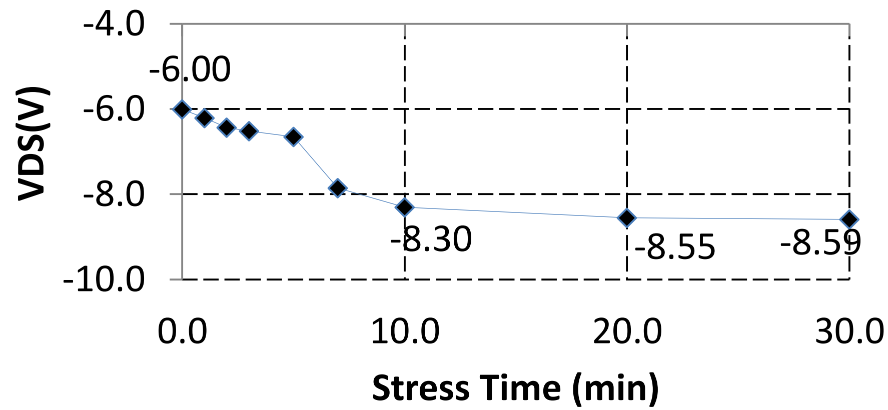
Stacking Faults Expansion



VON(Ids=200)



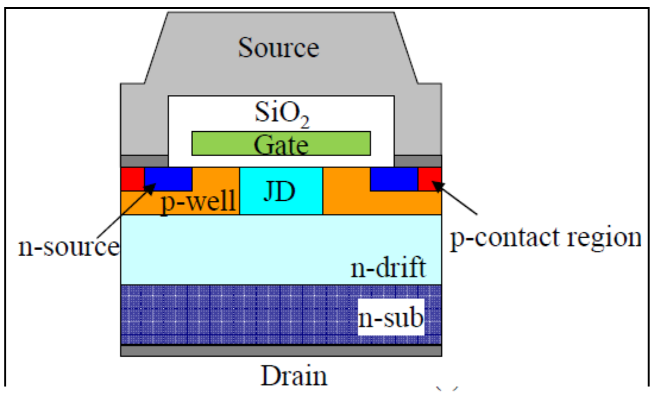
VF(Ids=200)

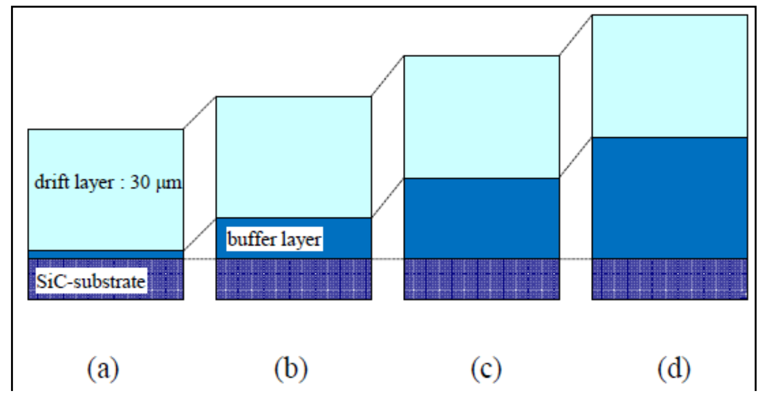


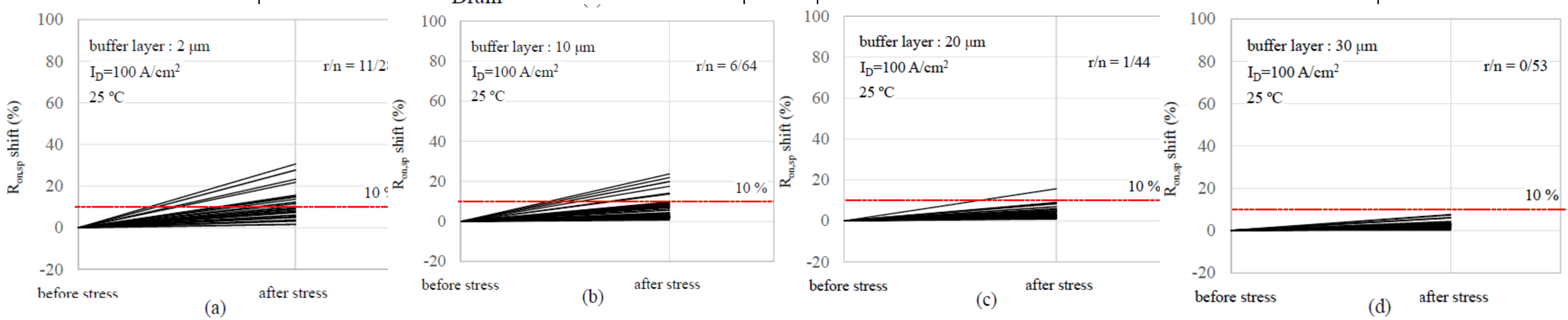
Effect of Thickness of Buffer layer to suppress the expansion of SFs

"Reliability Investigation with Accelerated Body Diode Current Stress for 3.3kV 4H-SiC MOSFETs with Various Buffer Epilayer Thickness"

3.3 kV 4H-SiC MOSFETs with various buffer layer thickness has been fabricated in order to investigate the bipolar degradation associated with the expansion of stacking faults.







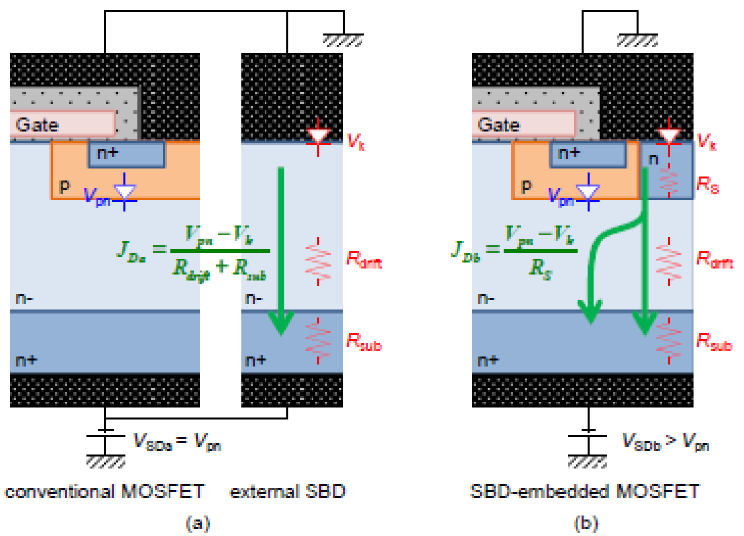
Y. Ebiike, et. al., Mitsubishi Electric Corporation, ISPSD (2018)

Embedded SBDs in planar SiC MOSFETs

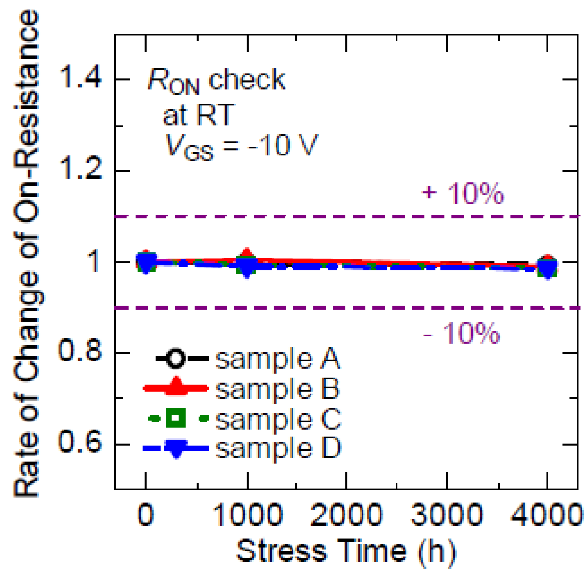
"6.5 kV Schottky-Barrier-Diode-Embedded SiC-MOSFET for Compact Full-Unipolar Module"

The purpose of this work is to remove external SBD chips from modules while maintaining device reliability to realize compact high Voltage SiC modules that are free from bipolar degradation."

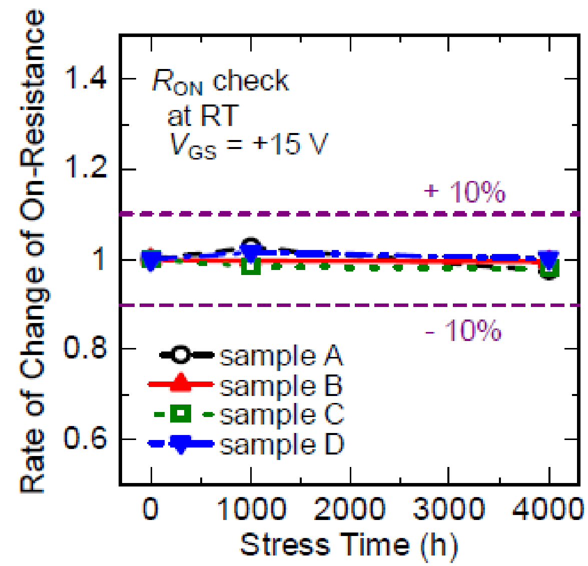
When voltages applied at pn junctions are equal to V_{pn},



V_{pn}: built-in potential of pn junction
V_k: Schottky voltage
J_{Da}: current density in (a)
J_{Db}: current density in (b)



(a) Diode conduction



(b) FET conduction

K. Kawahara, et. al., Mitsubishi Electric Corporation, ISPSD (2017)

SWITCH-MOS (SBD-wall integrated trench MOSFET)

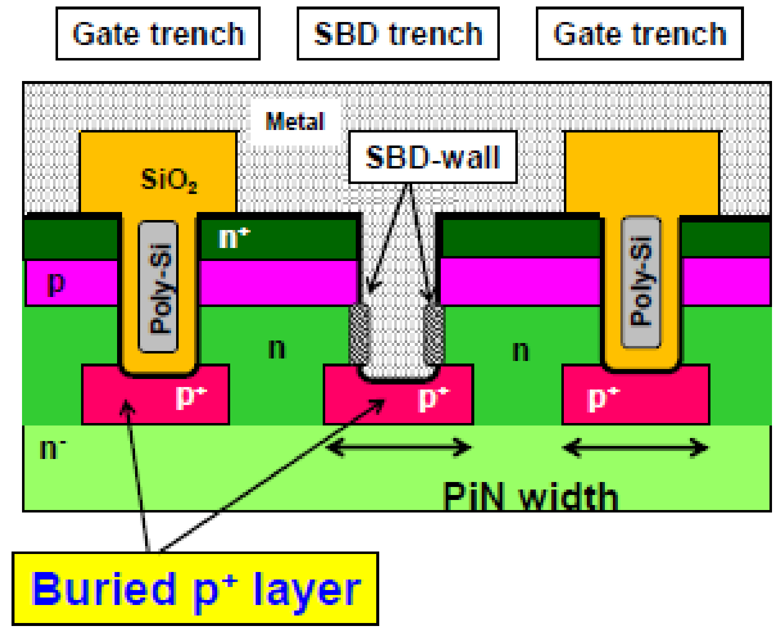
"Body-PiN-diode inactivation with low on-resistance achieved by a 1.2 kV-class 4H-SiC SWITCH-MOS"

The concept of SWITCH-MOS

Inactivation of body-PiN-diode by SBD-integration and low RonA

- ☺ low specific on-resistance (RonA)
  - ✓ Integration of trench SBD into trench MOSFET
- ☹ ~~high electric field at trench bottoms~~
- ☺ Low electrical field by buried p⁺ layer
- ☺ inactivation of body-PiN-diode until high current density
  - ✓ PiN width is narrow by trench structure

SWITCH-MOS (SBD-wall integrated trench MOSFET)

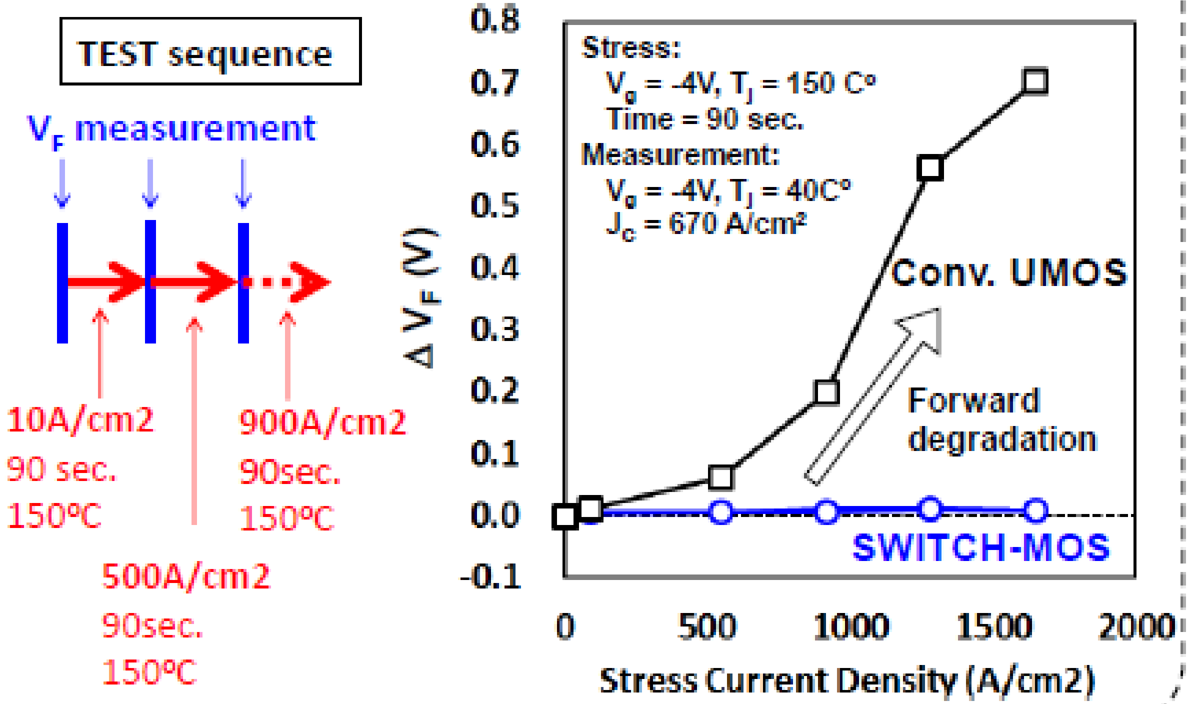


SWITCH-MOS has a potential to achieve inactivation of body-PiN-diode with low RonA

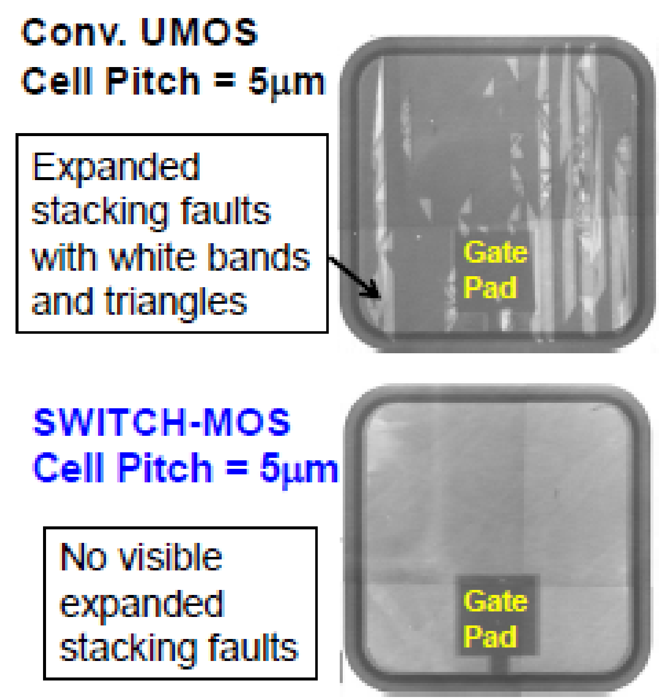
Y. Kobayashi, et. al., Fuji Electric Co. Ltd. and AIST, IEDM (2017)

Forward voltage degradation in SWITCH-MOS

Forward current stress test



PL mapping images after stress



SWITHC-MOS successfully suppress forward voltage degradation until high current density

Y. Kobayashi, et. al., Fuji Electric Co. Ltd. and AIST, IEDM (2017)

Contents

Summery

1. Automotive industry is facing profound transformation that comes only once in 100 years.

2. Toyota will strategically develop new values, “Electrification”, “Information” and “Intelligence”.

3. Toyota believes vehicle electrification is essential to reduce CO_2. We accelerate next-generation electrified vehicles development.

4. In order to expand SiC application on vehicles to contribute toward the reduction of CO_2, we have to reduce total cost of system. Low $R_{on}A$ device development and improving reliability are key activities for engineers and researches.