# Comparison of SiC MOSFET and Si IGBT

## Description

This document explains the comparison of Toshiba SiC MOSFET TW070J120B and Si IGBT, by switching loss, conduction loss, diode loss, and total power loss simulation.

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# 1. SiC Power Devices

Silicon carbide (SiC) comprises silicon (Si) and carbon (C) atoms. Each atom is surrounded by four different atoms in the form of a regular tetrahedron. SiC is a compound semiconductor with the densest tetrahedral arrangement. SiC has many crystalline structures called polytypes that exhibit different physical properties because of periodic differences in the overlap of tetrahedrons.

Compared to silicon, SiC has a wider energy gap where no electron states can exist (called a bandgap) between the valence band (i.e., an energy band filled with valence electrons) and the conduction band (i.e., an empty energy band in which electrons can be present). A wide bandgap provides a strong chemical bond among atoms and therefore a high electric breakdown field. SiC has an electric breakdown field roughly ten times that of silicon. Because of a strong atomic bond, SiC has greater lattice vibration and consequently conducts energy more easily than silicon. Therefore, SiC is a semiconductor material with good thermal conduction. The polytypes of SiC include 4H-SiC and 6H-SiC that are hexagonal crystal structures and 3C-SiC that is a cubic crystal structure. Table 1-1 compares the physical properties of silicon and other semiconductor materials. 4H-SiC is commonly used as a semiconductor material because it provides a better balance among electron mobility, dielectric breakdown strength, saturation velocity, and other physical properties than other polytypes of SiC.

**Table 1-1 Physical Properties of Typical Semiconductor Materials**

| Property | Unit | Si | 4H-SiC | 6H-SiC | 3C-SiC | GaN | GaAs | Diamond |
|---|---|---|---|---|---|---|---|---|
| Bandgap | eV | 1.12 | 3.26 | 3.02 | 2.23 | 3.39 | 1.43 | 5.47 |
| Electron mobility $\mu_e$ | $cm^2/Vs$ | 1400 | 1000<br>⊥ to c-axis<br>1200<br>\|\| to c-axis | 450<br>⊥ to c-axis<br>100<br>\|\| to c-axis | 1000 | 900 | 8500 | 2200 |
| Hole mobility $\mu_h$ | $cm^2/Vs$ | 600 | 120 | 100 | 50 | 150 | 400 | 1600 |
| Electric breakdown field $E_c$ | V/cm | $3.0\times10^5$ | $2.8\times10^6$ | $3.0\times10^6$ | $1.5\times10^6$ | $3.3\times10^6$ | $4.0\times10^5$ | $1.0\times10^7$ |
| Thermal conductivity λ | W/cmK | 1.5 | 4.9 | 4.9 | 4.9 | 2.0 | 0.5 | 20 |
| Saturated electron drift velocity $V_{sat}$ | cm/s | $1.0\times10^7$ | $2.2\times10^7$ | $1.9\times10^7$ | $2.7\times10^7$ | $2.7\times10^7$ | $2.0\times10^7$ | $2.7\times10^7$ |
| Relative dielectric constant ε | | 11.8 | 9.7<br>⊥ to c-axis<br>10.2<br>\|\| to c-axis | 9.7<br>⊥ to c-axis<br>10.2<br>\|\| to c-axis | 9.7 | 9.0 | 12.8 | 5.5 |

As shown in Table 1-2, the resistance of the drift region accounts for a large percentage of the on-resistance per area of high-voltage power devices. To reduce on-resistance, it is necessary to either increase the dopant concentration in the drift region or reduce its thickness. However, the dopant concentration is inversely proportional to the withstand voltage. In the case of silicon with low breakdown strength, it is impossible to further increase the dopant concentration without compromising the withstand voltage. It is also difficult to reduce the thickness of the drift region of a silicon device because the expansion of the depletion region could cause punch-through (between drain and source) when a reverse bias is applied across the drain and source. SiC power devices with breakthrough performance have been appearing lately because the dielectric breakdown strength of 4H-SiC is nearly ten times that of silicon as shown in Table 1-1. For example, the withstand voltage of a MOSFET can be simply expressed as:

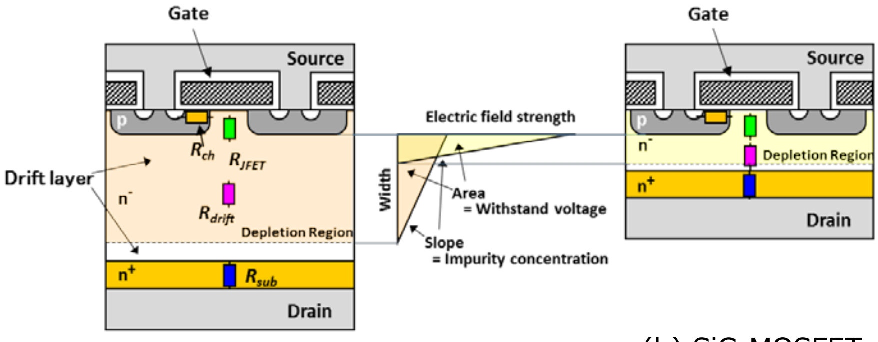
Withstand voltage = maximum electric breakdown field × depletion region thickness ÷ 2

(The assumption is a triangular electric field distribution.)

This equation indicates that because of a higher electric breakdown field than that of silicon, SiC makes it possible to increase the dopant concentration in the drift region and thereby reduce its thickness to obtain the same withstand voltage. Electron and hole mobilities (μ) characterize how quickly an electric field can accelerate the velocity of an electron or a hole (velocity = mobility (μ) × electric field (E)). A higher mobility (μ) means that an electric current flows more easily, resulting in lower resistance. The maximum velocity attainable is called the saturation velocity.

**Table 1-2 Simulated on-resistances of a double-diffused Si MOSFET**

| Withstand Voltage | 600V | 1000V |
|---|---|---|
| $R_{ch}$ | 1% | 0.3% |
| $R_{JFET}$ | 18% | 14% |
| $R_{drift}$ | 81% | 86% |
| $R_{sub}$ | 0.1% | 0.03% |
| TTL | 100% | 100% |




(a) Si-MOSFET (b) SiC-MOSFET

**Figure 1-1 Structure of a double-diffused MOSFET**

In addition, the high thermal conductivity (λ) of SiC makes it ideal as a material for high-power semiconductor devices.

SiC makes it possible to create high-voltage power devices with unprecedentedly low on-resistance thanks to a heavily doped thin drift region as shown in Figure 1-1 (b).

## 2. SiC MOSFET Features

Since the dielectric breakdown strength of SiC is about 10 times as high as that of Si, a power device with high withstand voltage and low voltage drop can be realized. In the case of the same withstand voltage, the on-resistance per unit area can be reduced compared with that of Si. In addition, while Si MOSFET is generally commercialized only up to about 1000V, SiC MOSFET is commercialized up to about 3300V because it can keep on-resistance low even at high withstand voltages. IGBT, the bipolar device, is commonly used as Si high-voltage transistors of 1000V or higher. IGBT have bipolar operation with two types of carriers, electron and hole, by injecting minority carriers, holes, into the drift layer, thereby lowering the resistance in the drift layer. However, the disadvantage of bipolar operation is that the tail current generated at turn-off due to the accumulation of minority carriers, which make increase turn-off loss.

On the other hand, SiC can realize MOSFET, the unipolar device that operates only with electrons even in high-voltage products, and the turn-off loss is smaller than bipolar devices because no tail current is generated. For this reason, SiC MOSFET is attracting attention because it can operate in the high switching frequency, which was difficult for Si IGBT, and it also contributes to the miniaturization of passive components.

This report makes comparison for the switching loss, conduction loss, and diode loss of SiC MOSFET and Si IGBT, and introduces examples of power loss simulation.

## 3. Power Loss Comparison of SiC MOSFET and Si IGBT

### 3.1 Rg-dependency of Turn-on and Turn-off Switching Loss (Note 1)

For both turn-on and turn-off switching loss, SiC MOSFET (TW070J120B) can reduce them compared to Si IGBT (Company A: High Speed Switching type).

(Note 1) IGBT test conditions:

$V_{CC}$=800 V, $I_C$=10 A, $T_a$=25 ºC, 150 ºC, $V_{GE}$ = 20 V / -5 V, Inductive Load: L = 1 mH,

IGBT emitter-to-collector diode is used as freewheeling diode (FWDs) in parallel with inductive load.

SiC MOSFET test conditions:

$V_{DD}$ = 800 V, $I_D$ = 10 A, $T_a$ = 25 ºC, 150 ºC, $V_{GS}$ = 20 V / -5 V, Inductive Load: L = 1 mH,

TW070J120B source-drain diode is used as freewheeling diode (FWDs) in parallel with inductive load.

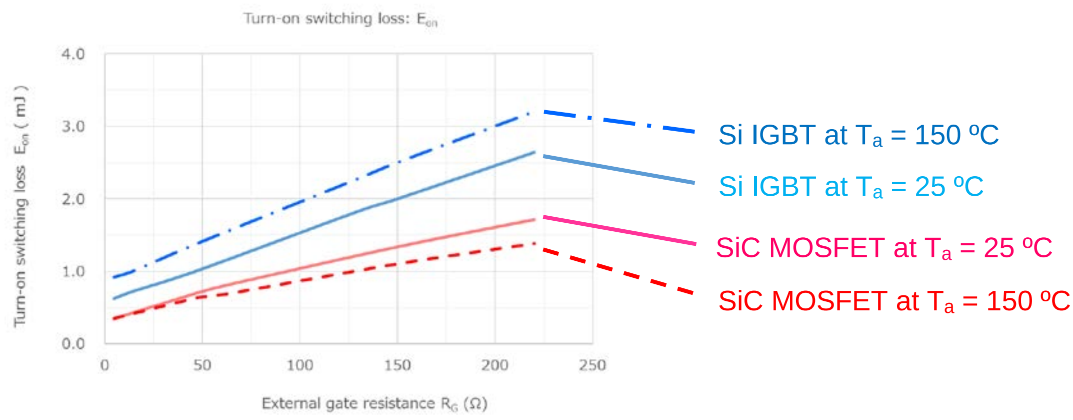



**Figure 3-1 SiC MOSFET and Si IGBT, Rg-dependency of turn-on switching loss**

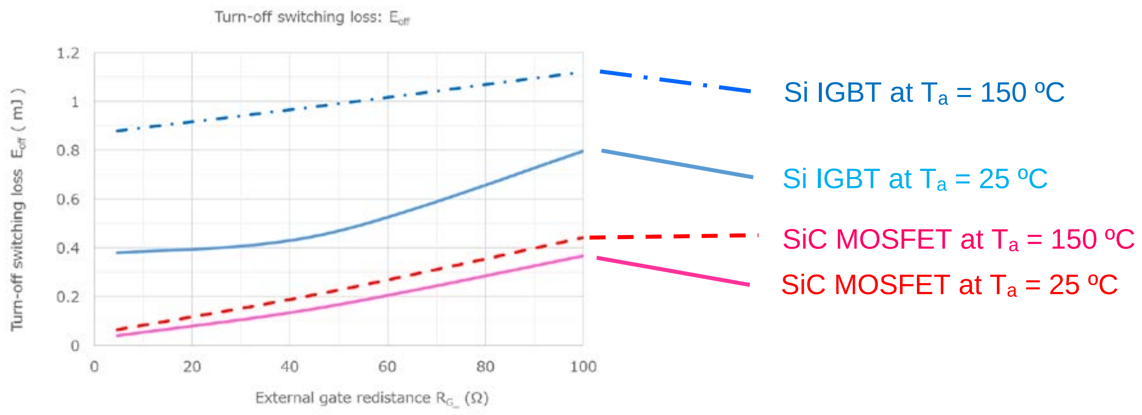



**Figure 3-2 SiC MOSFET and Si IGBT, Rg-dependency of turn-off switching loss**

## 3.2 Turn-on Switching Waveforms and Turn-on Switching Loss (Note2)

(Note 2)

IGBT test condition: external gate resistance $R_G$ = 150 Ω, others are the same test condition as (Note 1).

SiC MOSFET test condition: external gate resistance $R_G$ = 47 Ω; others are the same test condition as (Note 1).

In order to equalize current slope at turn-on, the test conditions is set as above.

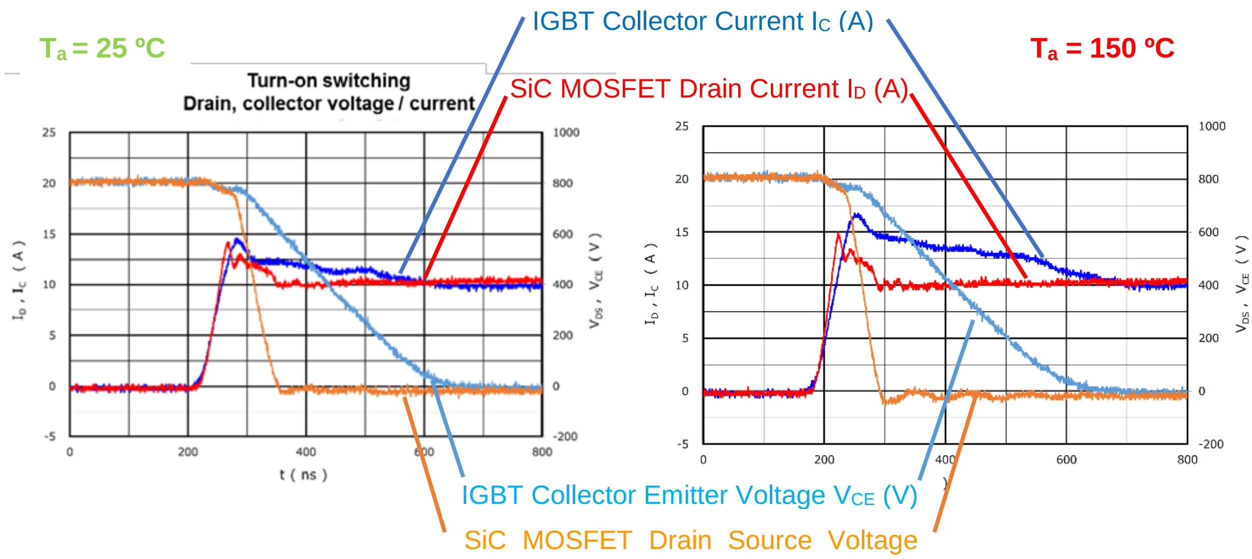



**Figure 3-3 Turn-on Switching Waveform of SiC MOSFET and Si IGBT**


**Figure 3-4 Turn-on Switching Loss of SiC MOSFET and Si IGBT**

| Turn-on switching-loss $E_{on}$ | $T_a$ = 25 ºC | $T_a$ = 150 ºC |
|---|---|---|
| $E_{on}$ of IGBT (mJ) | 2.0 | 2.5 |
| $E_{on}$ of SiC MOSFET (mJ) | 0.7 | 0.6 |
| From IGBT to SiC MOSFET $E_{on}$ reduction rate | 65% reduced | 76% reduced |

## 3.3 Turn-off Switching Waveform and Turn-off Switching Loss (Note3)

(Note 3) IGBT, SiC MOSFET test conditions:

The external gate resistor $R_G$ is 47 Ω. Otherwise, the test conditions are the same as (Note 1).

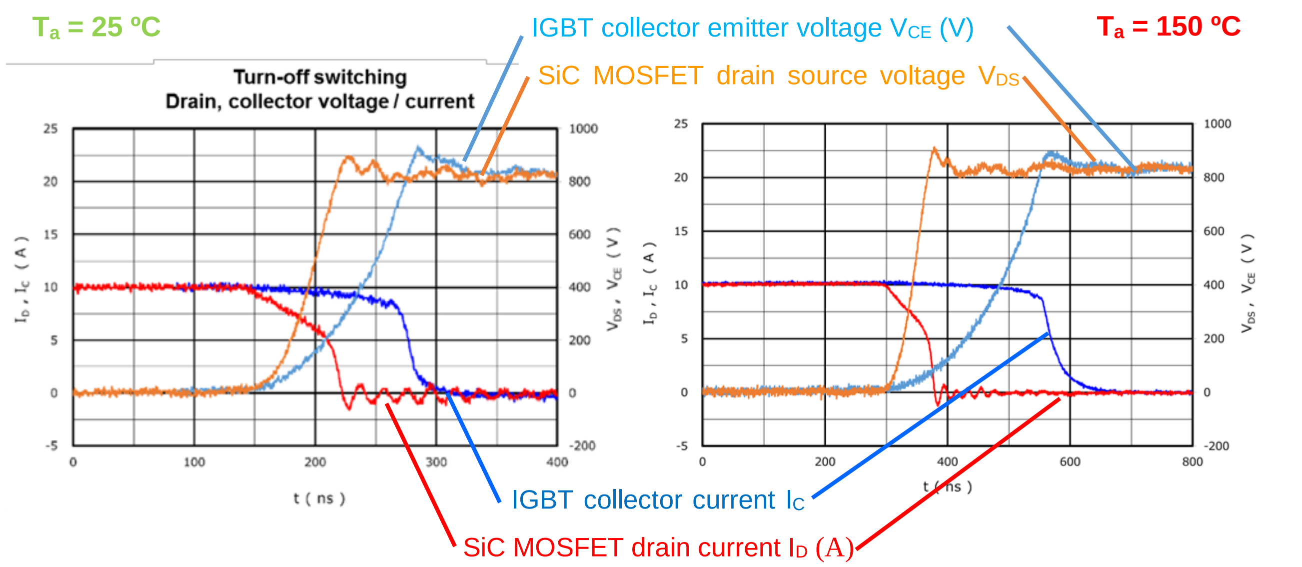



**Figure 3-5 Turn-off Waveform of SiC MOSFET and Si IGBT**

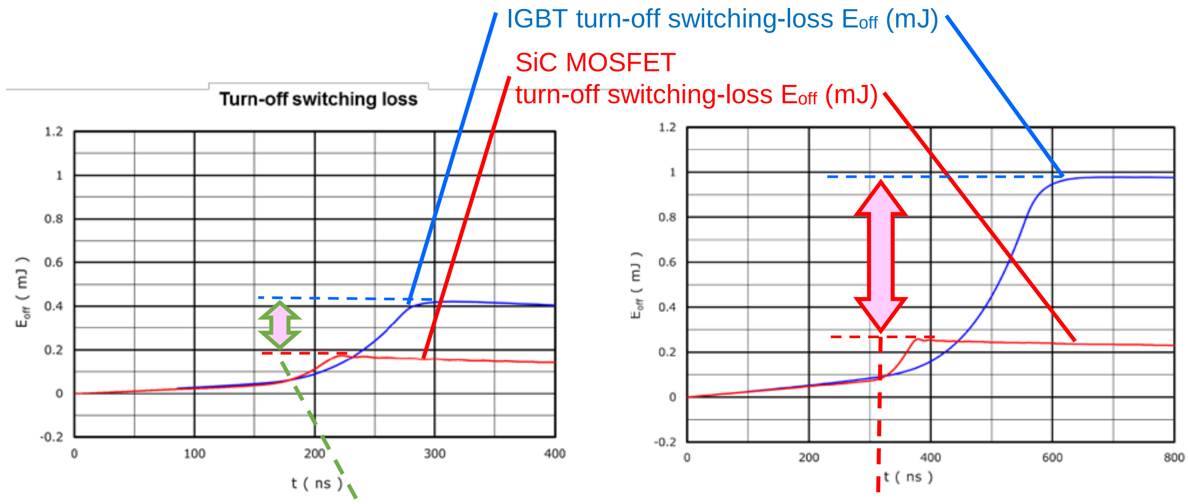



**Figure 3-6 Turn-off Switching Loss of SiC MOSFET and Si IGBT**

| Turn-off switching-loss $E_{off}$ | $T_a$ = 25 ºC | $T_a$ = 150 ºC |
|---|---|---|
| $E_{off}$ of IGBT (mJ) | 0.46 | 0.98 |
| $E_{off}$ of SiC MOSFET (mJ) | 0.16 | 0.22 |
| From IGBT to SiC MOSFET $E_{off}$ reduction rate | 65% reduced | 77% reduced |

## 3.4 On-resistance Characteristics

SiC MOSFET (TW070J120B) can reduce the on-voltage characteristic $V_{DS(on)}$ ($V_{CE(sat)}$) in the area below $T_a$ = 150 ºC, $I_D$ ($I_C$) = 25A compared to Si IGBT (Company A: High Speed Switching type).

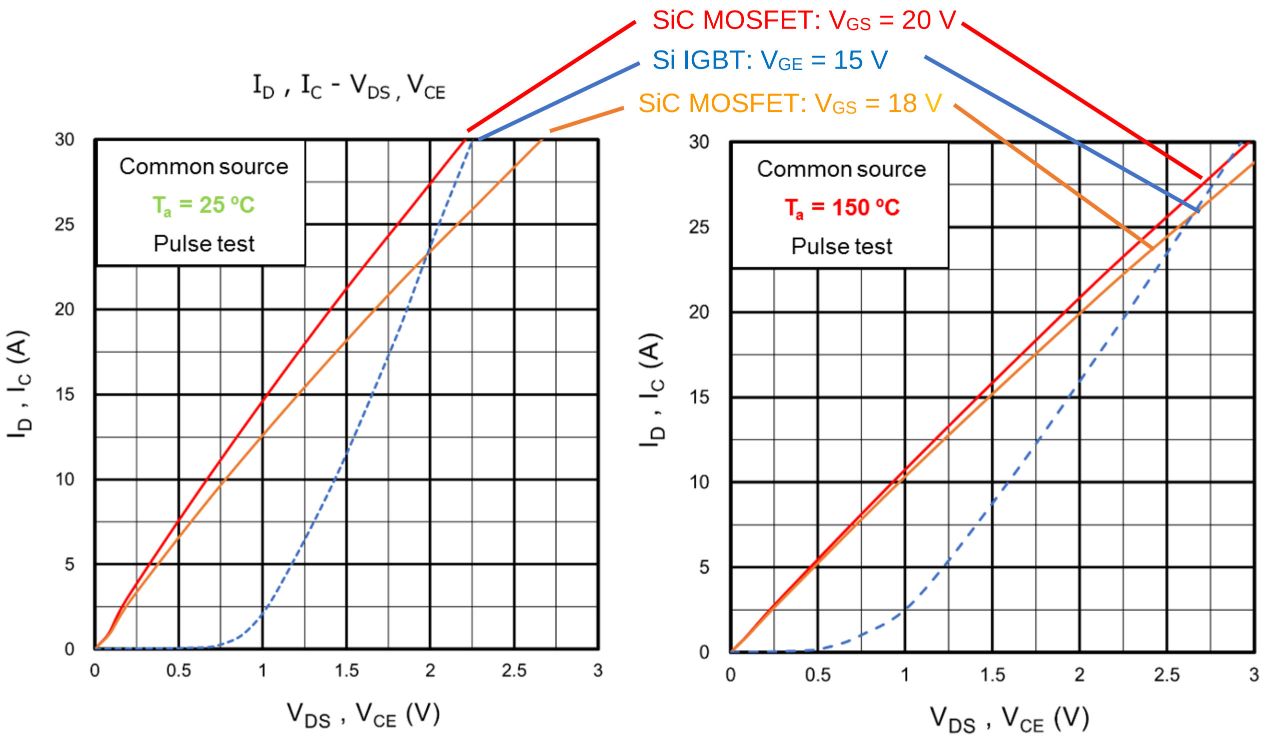



**Figure 3-7 $I_D$ - $V_{DS}$ Curve of SiC MOSFET and $I_C$ - $V_{CE}$ Curve of Si IGBT**

### 3.5 Diode Forward Voltage Characteristic

SiC MOSFET (TW070J120B) has a lower diode-forward voltage $V_F$ than Si IGBT (Company A: High Speed Switching type) when $T_a$ = 25 ºC, $I_F$ = 0.8 A or higher, and is comparable when $T_a$ = 150 ºC, $I_F$ = 3 A or higher.

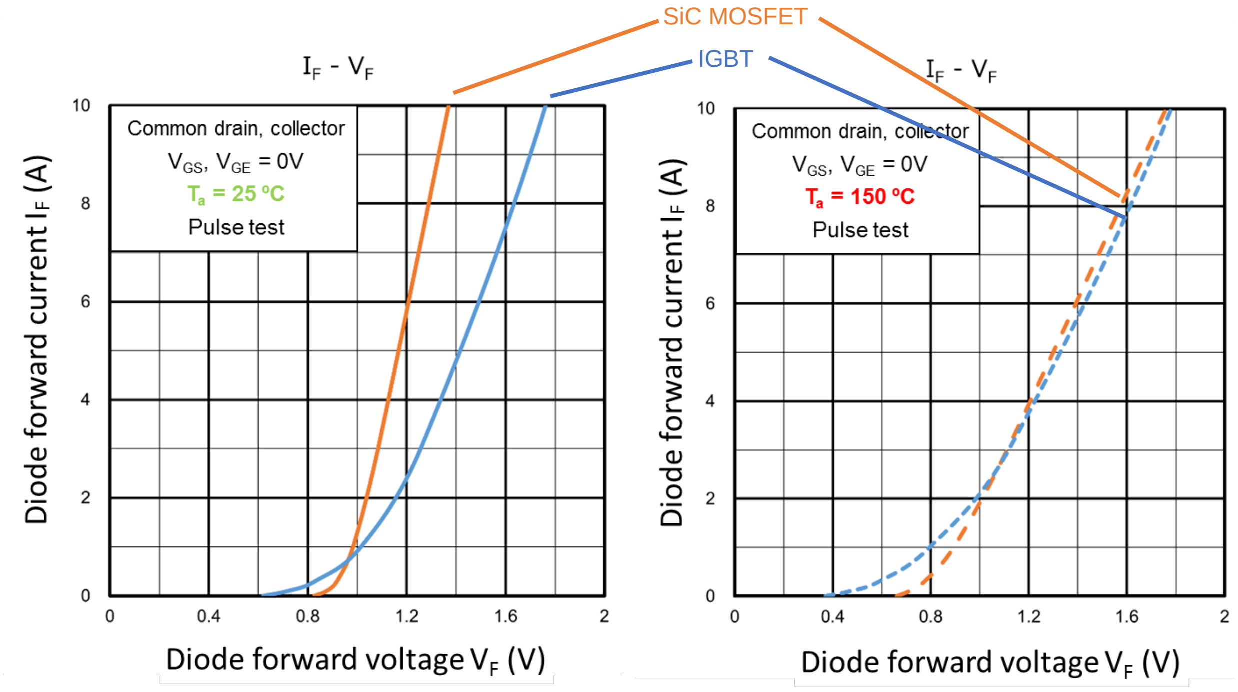



**Figure 3-8 $I_F$ - $V_F$ Curves of SiC MOSFET and Si IGBT**

## 4. Power Loss Simulation

Using the switching characteristics, on-resistance characteristics, and diode-forward voltage characteristics of SiC MOSFET (TW070J120B) and Si IGBT, Power Loss is simulated with conditions as $V_{cc}$ = 400V, $I_o$ = 7.0 Arms, P.F. = 1, three-phase modulation, and $T_j$ = 150 °C.
SiC MOSFET (TW070J120B) can reduce approximately 28W power loss compared to Si IGBT, contributing to efficiency improvement of equipment.

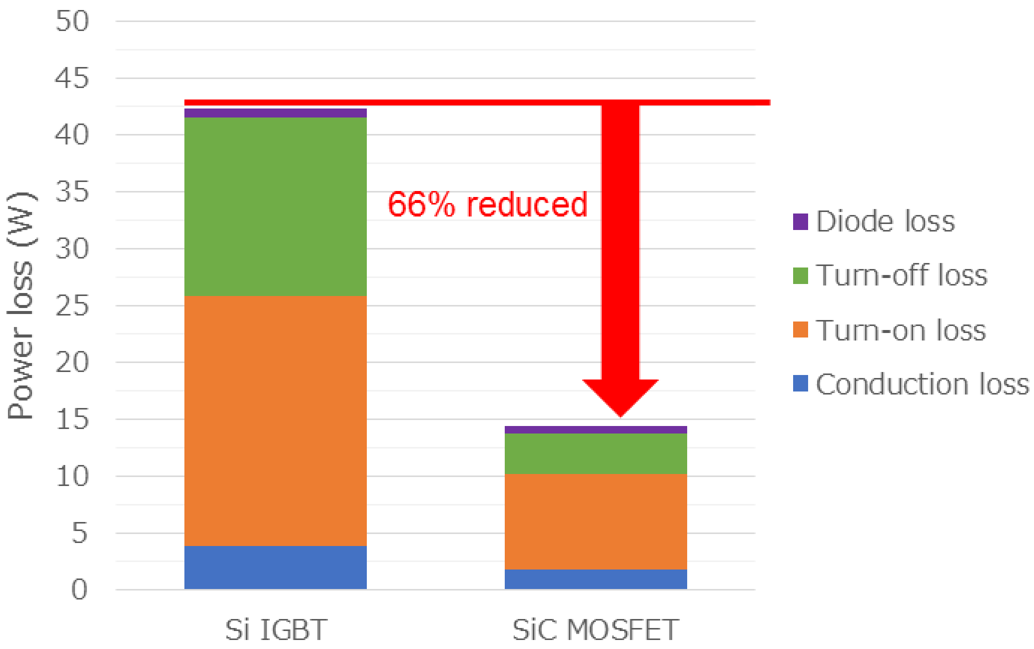



**Figure 4-1 Power Loss Simulation Results**

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