Chapter 6

Cooling Design

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This section explains the cooling design.

For safe IGBT operation, the junction temperature (Tj) must never exceed Tj(max). Therefore, it is necessary to have a cooling design capable of keeping the junction temperature below Tj(max), even during overload conditions.

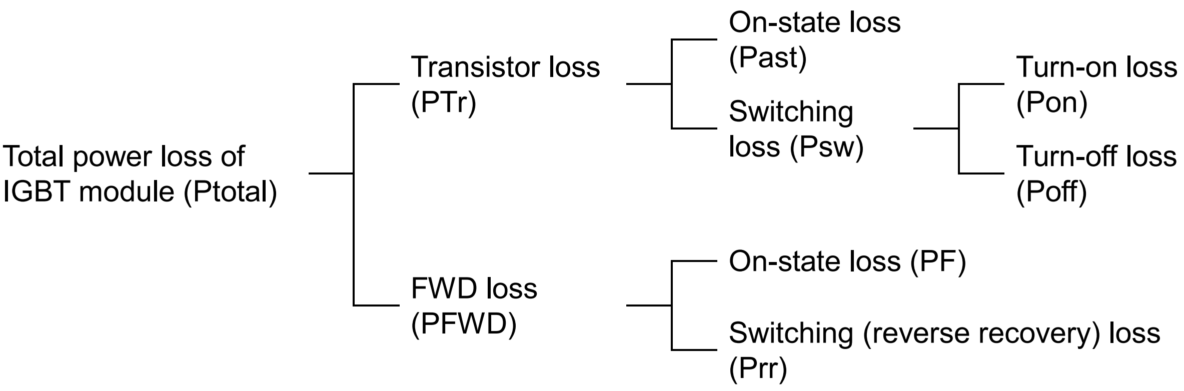
1 Power dissipation loss calculation

In this section, the simplified methods of calculating dissipation wattage for IGBT modules are explained below. However, the detailed calculation is available by the use of IGBT simulator on the Fuji Electric WEB site. You can calculate the dissipation wattage for various working condition of each package type module if you can get it.

1.1 Types of power loss

An IGBT module consists of IGBT chips and FWD chips. The sum of the power losses from these sections equals the total power loss for the module. Power loss can be classified as either on-state loss or switching loss. A diagram of the power loss factors is shown as follows.

Power loss factors



The on-state power loss from the IGBT and FWD sections can be calculated using the output characteristics, while switching loss can be calculated from switching loss vs. collector current characteristics. Use these power loss calculations in order to design cooling sufficient to keep the junction temperature Tj below the maximum rated value.

The on-voltage and switching loss values to be used here, are based on the standard junction temperature Tj (125°C is recommended).
For characteristics data, refer to the module specification sheets.

1.2 DC chopper circuit power loss calculations

For easy approximate calculations, consider the current flowing to the IGBT or FWD as a train of square waves. Fig.6-1 is a diagram showing the approximate waveforms of a DC chopper circuit. At collector current Ic the saturation voltage is represented by $V_{CE(sat)}$ and switching energy is represented by Eon and Eoff. At FWD forward current I_F, V_F represents the on- voltage and E_{RR} represents the energy loss during reverse recovery. Using the above parameters, IGBT power loss can be calculated as follows:

IGBT power dissipation loss (w) = On-state loss + Turn-on loss + Turn-off loss

$$= \left[t1/t2 \times V_{CE(sat)} \times I_C \right] + \left[fc \times \left(E_{on} + E_{off} \right) \right]$$

FWD power dissipation loss (w) = On-state loss + Reverse recovery loss

$$= \left[(1 - (t1/t2)) \times I_F \times V_F \right] + \left[fc \times E_{rr} \right]$$

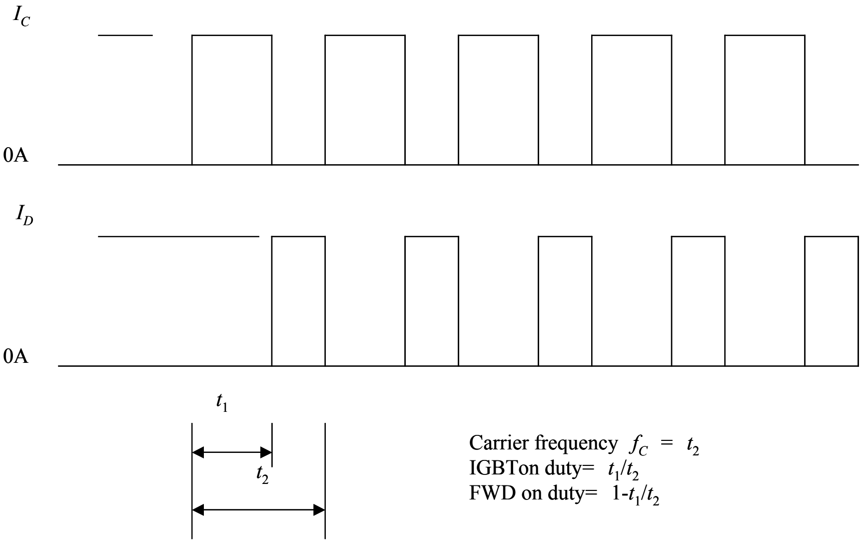


Fig. 6-1 DC chopper circuit current waveforms

The DC supply voltage, gate resistance, and other circuit parameters, may deviate from the standard value listed in the module specification sheets. In this event, approximate values can be calculated according to the following rules:

- DC supply voltage Ed(VCC) deviation
  On voltage: Not dependent on Ed(VCC)
  Switching loss: Proportional to Ed(VCC)

- Gate resistance deviation
  On voltage: Not dependent on gate resistance
  Switching loss: Proportional to switching time and dependent on gate resistance

1.3 Sine-wave VVVF inverter application power dissipation loss calculation

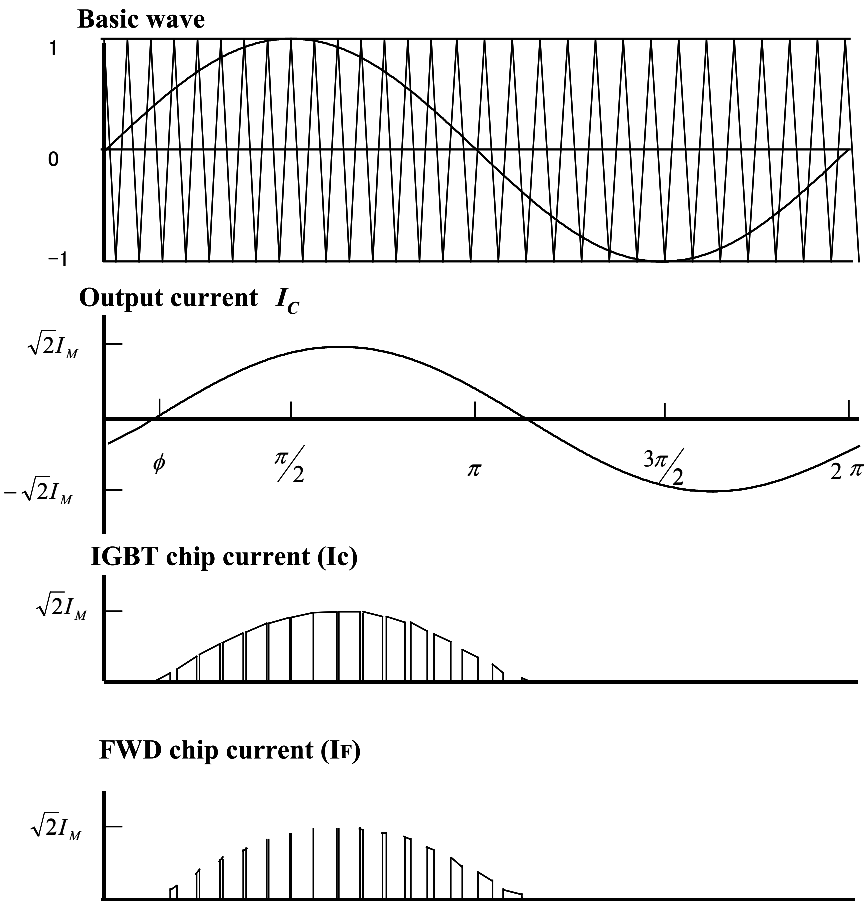


Fig. 6-2 PWM inverter output current

When using a VVVF inverter for a PWM control, the current value and operation keep changing as shown in Fig.6-2. Therefore, it is necessary to use computer simulations in order to make detailed power loss calculations. However, since computer simulations are very complicated, the following is an explanation of a simple method that generates approximate values.

Prerequisites

For approximate power loss calculations, the following prerequisites are necessary:

- Three-phase PWM-control VVVF inverter for sine-wave current output
- PWM control based on the comparison of sine-waves and sawtooth waves
- Output current in ideal sine-wave form

Calculating on-state power loss (Psat, P_F)

As displayed in Fig.6-3, the output characteristics of the IGBT and FWD have been approximated based on the data contained in the module specification sheets.

On-state power loss in IGBT chip (P_{sat}) and FWD chip (P_F) can be calculated as follows:

$$\left(P_{sat}\right) = DT\int_0^x I_C V_{CE(sat)} d\theta$$

$$= \frac{1}{2} DT\left[\frac{2\sqrt{2}}{\pi} I_M V_O + I_{M^2} R\right]$$

$$\left(P_F\right) = \frac{1}{2} DF\left[\frac{2\sqrt{2}}{\pi} I_M V_O + I_{M^2} R\right]$$

DT, DF: Average conductivity of the IGBT and FWD at a half wave of the output current. (Refer to Fig.6-4)

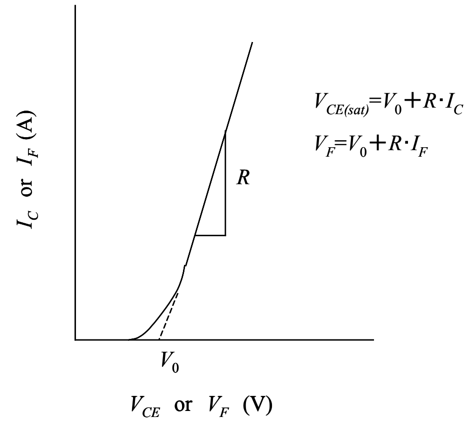


Fig. 6-3 Approximate output characteristics

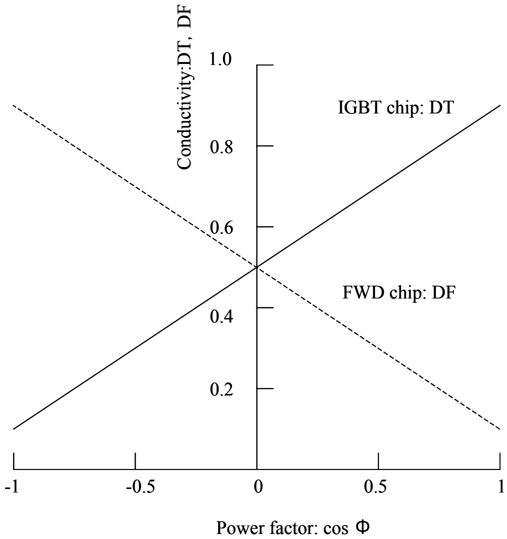


Fig. 6-4 Relationship between power factor sine-wave PWM inverter and conductivity

Calculating switching loss

The characteristics of switching loss vs. I_C are generally approximated using the following equations an Fig.6-5 (Module specification sheet data).

$$E_{on} = E_{on'}\left(I_C / ratedI_C\right)^a$$

$$E_{off} = E_{off'}\left(I_C / ratedI_C\right)^b$$

$$E_{rr} = E_{rr'}\left(I_C / ratedI_C\right)^c$$

a, b, c: Multiplier
Eon', Eoff', Err': Eon, Eoff and Err at rated IC

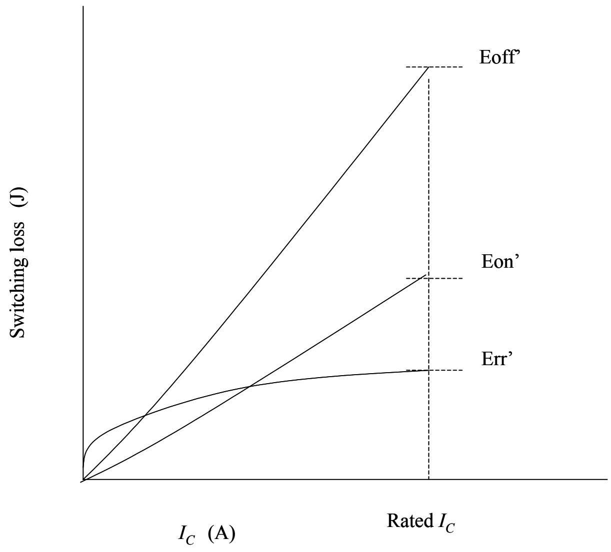


Fig. 6-5 Approximate switching losses

The switching loss can be represented as follows:

- **Turn-on loss (P_{on})**

$$P_{on} = fo\sum_{K=1}^{n}\left(E_{on}\right)k \qquad \left(n: Half - cycle\ switching\ count = \frac{fc}{2fo}\right)$$

$$= foE_{on}'\frac{1}{rated\ I_{C^a}}\sum_{k=1}^{n}\left(I_{C^a}\right)k$$

$$= foE_{on}'\frac{n}{rated\ I_{C^a} \times \pi}\int_0^{\pi}\sqrt{2}I_{M^a}\sin\theta d\theta$$

$$\fallingdotseq foE_{on}'\frac{1}{rated\ I_{C^a}}nI_{M^a}$$

$$= \frac{1}{2}fcE_{on}'\left[\frac{I_M}{rated\ I_C}\right]^a$$

$$= \frac{1}{2}fcE_{on}\left(I_M\right)$$

E_{on}(IM):Ic= E_{on} at I_M

- **Turn-off loss (P_{off})**

$$P_{off} \fallingdotseq \frac{1}{2}fcE_{off}\left(I_M\right)$$

$E_{off}(I_M)$:Ic= E_{off} at I_M

- **FWD reverse recovery loss (P_{rr})**

$$P_{off} \fallingdotseq \frac{1}{2} fcE_{rr}(I_M)$$

$E_{rr}(I_M)$:I_c= E_{rr} at I_M

Calculating total power loss

Using the results obtained in section 1.3 subsection 2 and 3.

IGBT chip power loss: $P_{Tr} = P_{sat} + P_{on} + P_{off}$

FWD chip power loss: $P_{FWD} = P_F + P_{rr}$

The DC supply voltage, gate resistance, and other circuit parameters will differ from the standard values listed in the module specification sheets.

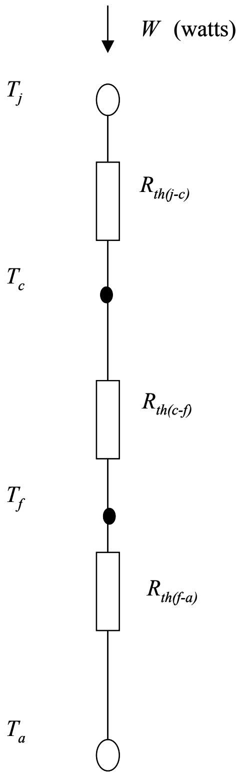
Nevertheless, by applying the instructions of this section, the actual values can easily be calculated.

2 Selecting heat sinks

Most power diodes, IGBTs, transistors and other power devices are designed to be insulated between electrodes and mounting bases. This type of module can be mounted and wired compactly in a variety of equipment, because several devices can be mounted in a single heat sink. However, in order to ensure safe operation, the power loss (heat) generated by each module must be dissipated efficiently. This is why heat sink selections is very important. The basic of heat sink selection will be illustrated in the following.

2.1 Thermal equations for on-state power loss calculations

The heat conduction of a semiconductor can be simulated in an electric circuit. For this example, with only one IGBT module mounted on the heat sink, the equivalent circuit is shown in Fig.6-6



W: Module power loss

T_j: Junction temperature if IGBT chip

T_c: Module case temperature

T_f: Temperature of heat sink (Temperature closest to the mounting position of the module)

T_a: Ambient temperature

$R_{th(j-c)}$: Thermal resistance between case and heat sink

$R_{th(c-f)}$: Contact thermal resistance between case and heat sink

$R_{th(f-a)}$: Thermal resistance between heat sink and ambient air

Fig. 6-6 Thermal resistance equivalent circuit

Using the above equivalent circuit, the junction temperature (Tj) can be calculated using the following thermal equation:

$$Tj = W \times \left\{Rth(j-c) + Rth(c-f) + Rth(f-a)\right\} + Ta$$

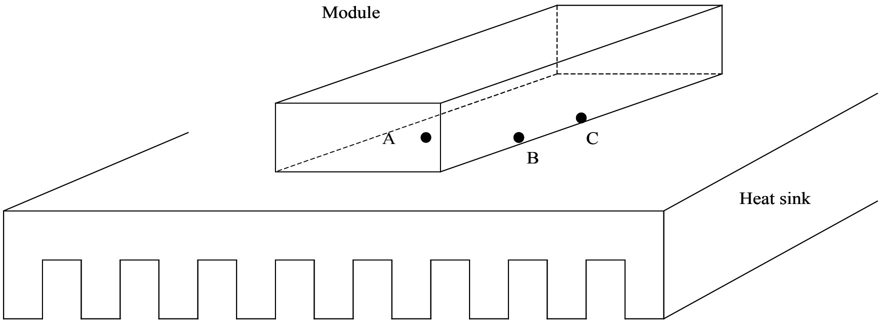
Note that the case temperature (T_c) and heat sink surface temperature mentioned here are measured from the base of the IGBT module directly below the chip. As shown in Fig.6-7, the temperature measurements at all other points may be low due to the heat dissipation capability of the heat sink, and this needs to be taken into consideration during final heat sink selection.

Next, the equivalent circuit of an IGBT (2-pack-module) and a diode bridge mounted on a heat sink is shown in Fig.6-8. The thermal equations in this case are as follows:

$$Tj(d) = Wd \times \left[Rth(j-c)d + Rth(c-f)d\right] + \left[(Wd + 2WT + 2WD) \times Rth(f-a)\right] + Ta$$
$$Tj(T) = WT \times Rth(j-c)T + \left[(WT + WD) \times Rth(c-f)T\right] + \left[(Wd + 2WT + 2WD) \times Rth(f-a)\right] + Ta$$
$$Tj(D) = WD \times Rth(j-c)D + \left[(WT + WD) \times Rth(c-f)T\right] + \left[(Wd + 2WT + 2WD) \times Rth(f-a)\right] + Ta$$

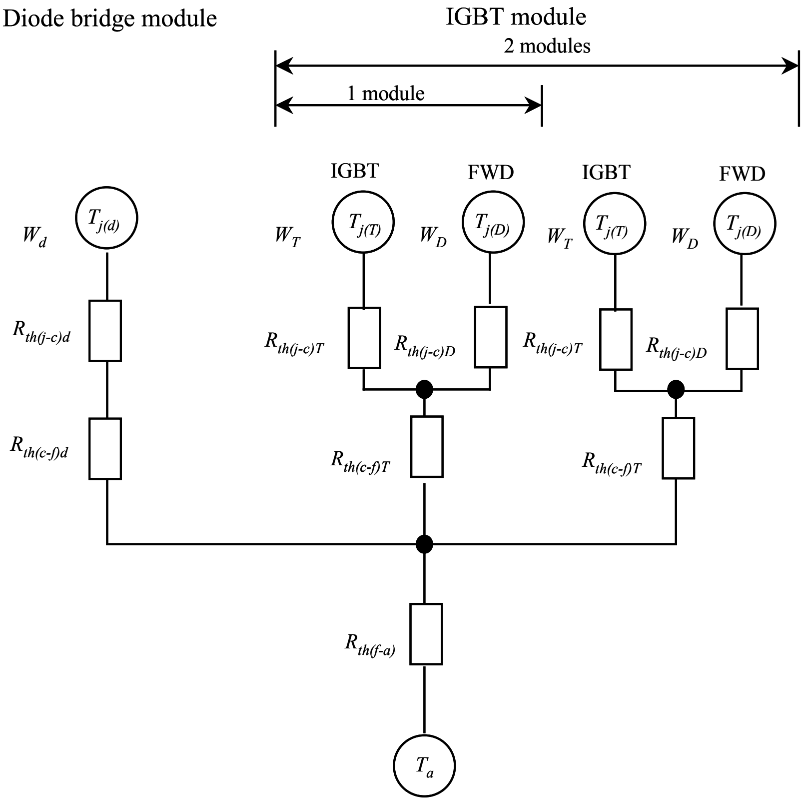
Use the above equations in order to select a heat sink that can keep the junction temperature (T_j) below T_j(max).

A : Directly below the chip by the case
B : Base, 14mm from point A
C : Base, 24mm from point A



	Point A	Point B	Point C
T_C (°C)	51.9	40.2	31.4
T_f (°C)	45.4	36.9	30.2

Fig. 6-7 Example of case and heat sink temperature measurement



W_d, $T_{j(d)}$,$R_{th(\ )d}$: Diode bridge (For one module)
W_T, $T_{j(T)}$, $R_{th(\ )T}$: IGBT (Each element)
W_D, $T_{j(D)}$, $R_{th(\ )D}$: FWD (Each element)

Fig. 6-8 Thermal resistance equivalent circuit

2.2 Thermal equations for transient power loss calculations

In general, as before, it is all right to base the on-state T_j on the average power loss. However, in actuality, repetitive switching causes power loss to pulse and the occurrence of temperature ripples as shown in Fig.6-10.

First consider the power loss as a train of constant cycles, and constant-peak square pulses. Then calculate the approximate peak of the temperature ripples using the transient thermal resistance curve given in the module specification sheets.

Be certain to select a heat sink that will also keep the T_{jp} below T_j (max).

$$Tjp - T_C = P \times \left[R(\infty) \times \frac{t1}{t2} + \left(1 - \frac{t1}{t2}\right) \times R(t1+t2) - R(t2) + R(t1) \right]$$

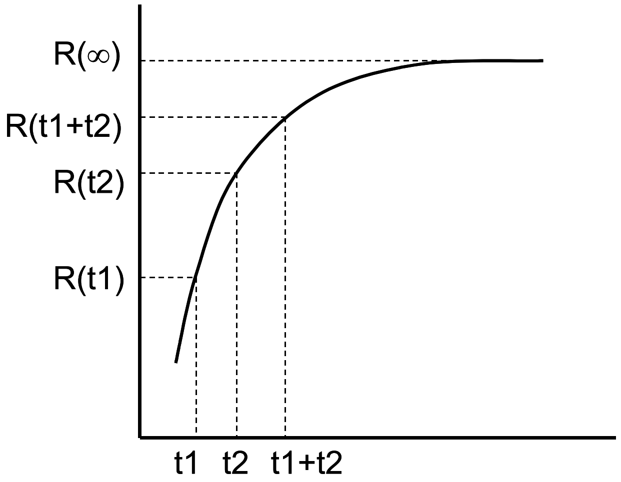


Fig. 6-9 Transient thermal resistance curve

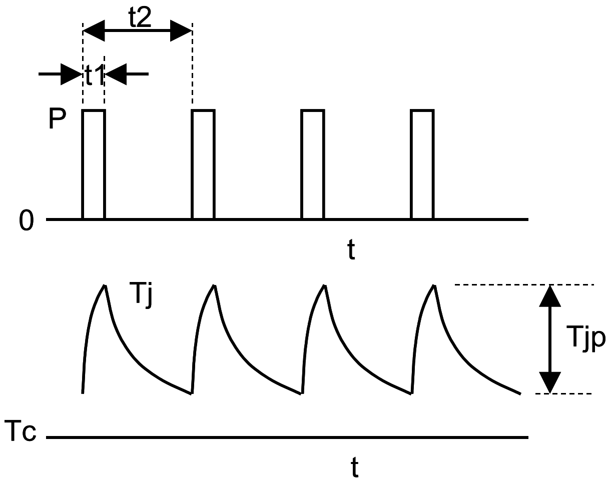


Fig. 6-10 Thermal ripples

3 Heat sink mounting precautions

3.1 Heat sink mounting

Since thermal resistance varies according to an IGBT's mounting position, pay attention to the following points:

- When mounting only one IGBT module, position it in the exact center of the heat sink in order to minimize thermal resistance.
- When mounting several IGBT modules, determine the individual position on the heat sink according to the amount of heat that each module generates. Allow more room for modules that generate more heat.

3.2 Heat sink surface finishing

The mounting surface of the heat sink should be finished to a roughness of 10μm or less and a warp of 50μm or less for every distance of 100mm. If the surface of the heat sink is not flat enough, there will be a sharp increase in the contact thermal resistance (Rth(c-f)). If the flatness of the heat sink does not meet the above requirements, then attaching (clamping) an IGBT to it will place extreme stress on the DBC substrate situated between the module's chips and metal base, possibly destroying this insulating material.

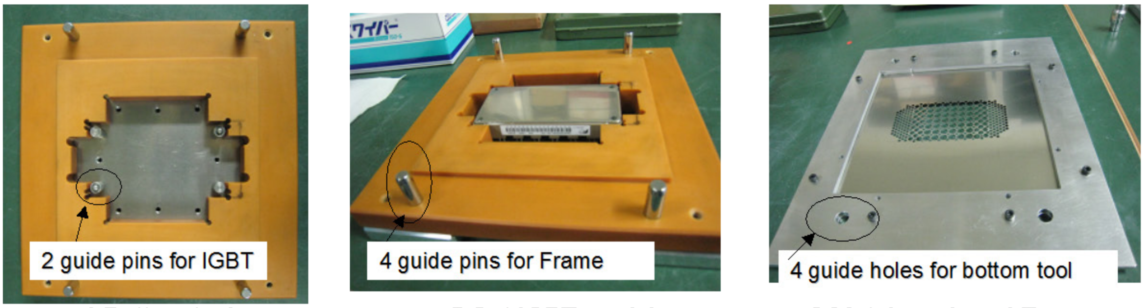
3.3 Thermal paste application

To reduce contact thermal resistance, we recommend applying a thermal paste between the heat sink and the IGBT's base plate.

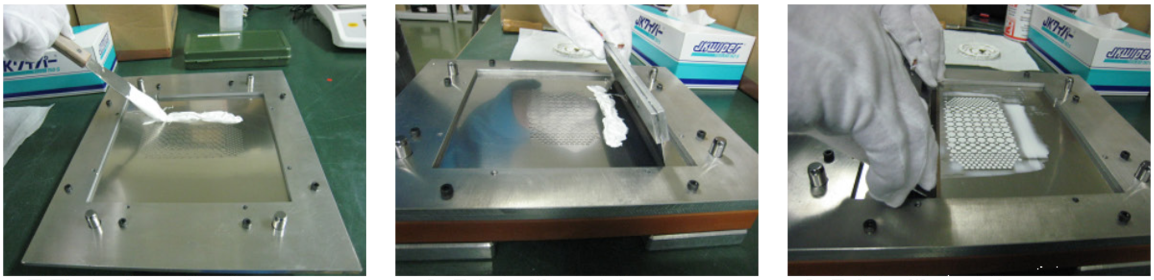
There are several methods of thermal paste application using roller or stencil mask and so on. Thermal paste helps the conductivity from IGBT modules to heat sink, but it has also thermal capacity. Therefore, too thick thermal paste is applied to conduct the heat towards the heat sink, results in raising the chip temperature. On the other hand, too thinner thermal paste application also results in raising the chip temperature as well, because of air gap between thermal paste and heat sink caused by heat sink roughness or warp. Therefore, you must apply thermal paste in the suitable thickness, or over-heating the silicon chip extremely above Tj(max) would break down IGBT modules in the worst operation. From these reason, thermal paste application with the use of stencil mask would be recommended to help the uniform application on the backside of modules.

Figure 6-11 shows the schematic view of the thermal paste application using a stencil mask. In the basic method, the specified weight of thermal paste is applied to the metal base surface of the IGBT module through a stencil mask. Subsequently fix the IGBT module on the heat sink by tightening the screws with the torque recommended for respective products. In this way, the thermal paste is applied uniformly. Fuji Electric can supply our recommended stencil mask drawing according to customer's request.

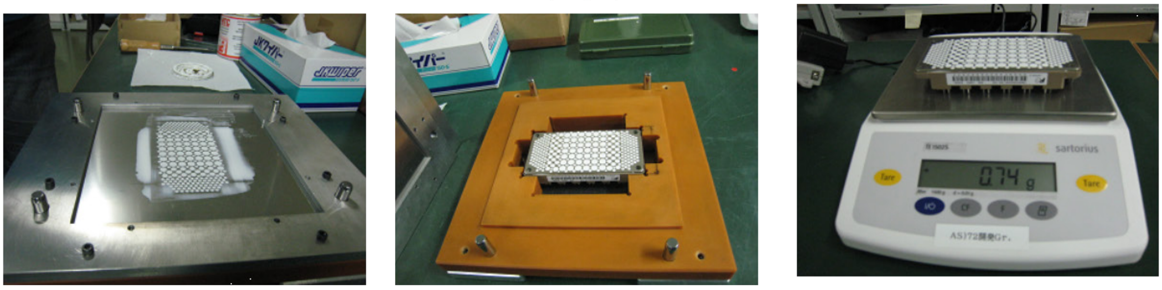
1.Back to Room Temp. 2.Mesure weight of IGBT 3.Adjust zero



4.Bottom tool 5.Set IGBT module 6.Metal mask and Frame



7.Fix tools and put grease with Knife 8. Print with metal squeegee (begin) 9. Print with metal squeegee (end)



10.After printing 11. Open metal mask 12. Check grease weight

Fig. 6-11 Schematic view of thermal paste application example

If the thermal grease is applied uniformly, the required weight can be calculated as follows.

$$\text{Thermal grease thickness (um)} = \frac{\text{Weight of thermal grease (g)} \times 10^4}{\text{Base area of module (cm}^2\text{)} \times \text{Density of thermal grease (g/cm}^3\text{)}}$$

Obtain the necessary thickness of thermal grease from this formula and apply the thermal grease of that weight to the module. The recommended thickness of applied thermal grease is about 100um.

However, the optimal thickness of thermal paste differs depending on the paste characteristics and the application method and so check them before use.

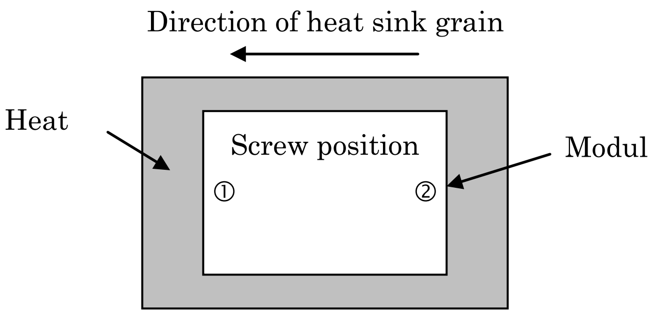
The recommended thermal pastes are shown in Table 6-1.

Table 6-1 Example of thermal paste

Product name	Manufacturer
G746	Shin-Etsu Chemical Co., Ltd.
TG221	Nihon Data Material Co.,
SC102	Toray Dow-Corning Co., Ltd.
YG6260	Toshiba Silicone Co., Ltd.
P12	Wacker Chemie.
HTC	ELECTROLUBE.

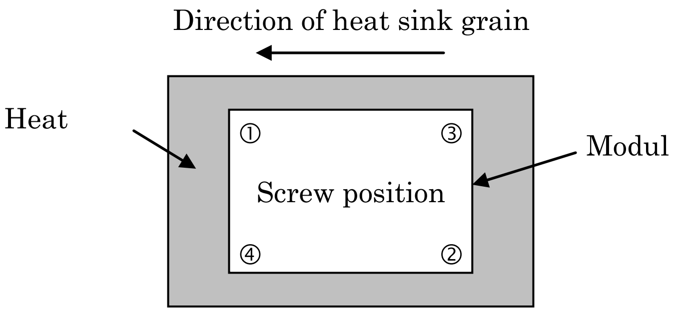
3.4 Mounting procedure

Figure 6-12 diagrams show how to tighten an IGBT module's mounting screws. Each screw must be tightened using a specified torque. For the proper tightening torque, refer to the module specification sheets. An insufficient tightening torque may cause the contact thermal resistance to increase or the screws to come loose during operation. On the other hand, an excessive tightening torque may damage the IGBT's case.



	Torque	Sequence
Initial	1/3 specified torque	①→②
Final	Full specified torque	②→①

(1) Two-point mounting



	Torque	Sequence
Initial	1/3 specified torque	①→②→③→④
Final	Full specified torque	④→③→②→①

(2) Four-point mounting

Fig. 6-12 IGBT module clamping

3.5 IGBT module mounting direction

When mounting the IGBT module, it is recommended to place the module lengthwise in the direction of the heat sink’s grain. This reduces the effects of changes in the heat sink’s shape.

3.6 Temperature verification

After deciding on a heat sink and mounting positions, measure the temperature of each area, and confirm that the junction temperature (T_j) of each module is within the required range.

For reference, Fig.6-12 is a diagram of how to measure the case temperature (T_c).

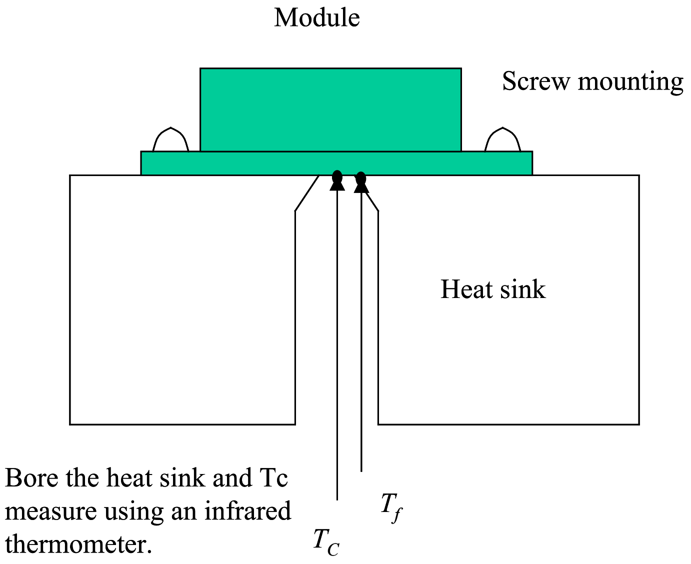


Fig. 6-13 Measurement of case temperature (Tc)

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