Technique for Thermal Resistance Measuring of Heat-Sink in the Linear Mode

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บทคัดย่อ

วัตถุประสงค์ของบทความนี้มิได้กล่าวถึงการออกแบบแผ่นระบายความร้อน หากแต่เป็นการอธิบายถึงวิธีในการวัดหาค่าความต้านทานความร้อนของแผ่นระบายความร้อนที่ไม่มีแผ่นข้อมูลประกอบ ในบทความนี้พยายามที่จะอธิบายที่มาของความสัมพันธ์บนพื้นฐานของทฤษฎีบทการถ่ายเทความร้อนที่ไม่ยาก และนำเสนอวิธีการง่ายๆ ในทางปฏิบัติที่จะวัดหาค่าความต้านทานความร้อนของแผ่นระบายความร้อนดังกล่าว หลักการสำคัญคือการทำงานภายใต้แหล่งอุณหภูมิที่รับรู้ได้สองจุด โดยการวัดอุณหภูมิของแผ่นระบายความร้อน และอุณหภูมิของอากาศโดยรอบ ในการที่จะหาค่าของความต้านทานความร้อนของแผ่นระบายความร้อน ($R_{\theta sa}$) แหล่งกำเนิดความร้อนจะถูกกำเนิดโดย IGBT ที่ทำงานในโหมดเชิงเส้น และติดตั้งบนแผ่นระบายความร้อนที่จะทดสอบ ปริมาณความร้อนที่ถูกผลิตโดย IGBT ในโหมดเชิงเส้น อุณหภูมิของแผ่นระบายความร้อน และอุณหภูมิของอากาศโดยรอบแผ่นระบายความร้อน จะสามารถนำมาหาค่าของความต้านทานความร้อนของแผ่นระบายความร้อนได้จากความสัมพันธ์ง่ายๆ คือ $R_{\theta sa}= (T_s-T_a)/P_d$ จากหลักการนี้เองเราก็จะสามารถที่จะวัดค่าความต้านทานความร้อนของแผ่นระบายความร้อนที่ไม่มีแผ่นข้อมูลประกอบได้โดยง่าย

คำสำคัญ: ความต้านทานความร้อน การถ่ายเทความร้อน แผ่นระบายความร้อน

Abstract

The objective of this article was not to design a heat-sink, but to describe the measurement of thermal resistance of the heat-sink with no supporting information. This paper has attempted to explain a simple relationship based on heat transfer theory, and to demonstrates an easy, practical method of measuring the thermal resistance of the heat-sink. The principle is to operate under two known temperature conditions by monitoring the temperature of heat-sink and ambient temperature in a steady-state condition. In order to ascertain the heat-sink's thermal resistance ($R_{\theta sa}$), the heat source was generated by the IGBT operating in a linear mode and installed on a test specimen. Heat generated by the IGBT operating in a linear mode and the temperature of this heat-sink and that of the ambience can estimate the $R_{\theta sa}$ of the heat-sink using the simple relationship $R_{\theta sa}=(T_s-T_a)/P_d$. From these procedures, we were able to measure easily the thermal resistance of a heat-sink with no datasheet.

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1. Introduction

Currently, the temperature in many modern power electronics applications has become an important factor when designing a system with high power. The losses can heat up the device's junction temperature above its maximum level ($T_{j(max)}$) and cause the system to fail. A good thermal design is a solution for preventing this situation. The junction temperature of the power device must be calculated not to exceed the $T_{j(max)}$ specified in the datasheet. A conventional method to pump heat from power devices is the use of a heat-sink as shown in Fig.1, and the concept of using a heat-sink is the heat transfer theory. If designers use the appropriate factors to design a heat-sink, it would make the system stable.

Unfortunately, many heat-sinks in Thailand do not come with a datasheet for a designer, thus causing one important parameter loss, which is the, $R_{\theta sa}$. The $R_{\theta sa}$ is one of the most important factors in managing the temperature of power devices and many designers do not consider this factor. Many power electronics designs in Thailand handle the thermal management by senses. Many of them think that the larger the heat-sink they use the better heat transfer they will get. Sometimes, they compare international markets via the Internet in order to use the $R_{\theta sa}$ to the nearest. However,this is not the correct thermal resistance of the heat-sink and the temperature management of devices is inappropriate and risks system failure. The following procedure will lead to the meausurement of the thermal resistance ($R_{\theta sa}$) of a heat-sink.

2. Heat Transfer Basic

Heat transfer will be taken into consideration when two surfaces of the medium have different temperatures and from the fact that, heat energy will transfer from a hotter surface to a colder one. A thermal circuit can be compared to an electrical circuit whereas the voltage is similar to the temperature and the current is similar to the heat as shown in Fig.2 [1].

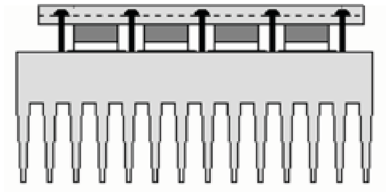

Figure 1 Power devices and its heat pump.

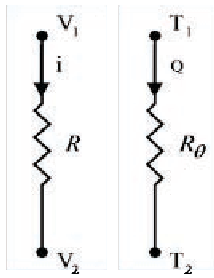

Figure 2 Thermal circuit and Electrical circuit.

From Fig.2 we can say that if the temperature difference is increased, the amount of heat flow will be increased and for the opposing heat flow factor this can be referred to as the thermal resistance (R_θ) of medium resulting in from the relationship:

$$Q = \frac{T_1 - T_2}{R_\theta} \quad (1)$$

the thermal resistance is :

$$R_\theta = \frac{\Delta T}{Q} \quad {}^oC/W \quad (2)$$

Thermal resistance (R_θ) is defined as the difference in temperature between two closed isothermal surfaces divided by the total heat flow between them and differs from thermal resistivity. Thermal resistivity is a material property and is not affected by the geometry of the thermal flux network in which the material is used. By contrast, thermal resistance is a function of the material resistivity and its geometry. Thermal resistivity is used for evaluating the thermal quality of a material to be used in component packaging applications. Thermal resistance is a figure of merit for evaluation of the thermal transport capability of component packaging. [1]

Considering the basic theorem of heat transfer, there are three modes of heat transfer [2]:

1) Conduction mode

2) Convection mode and

3) Radiation mode

When the concept of the heat pump for power devices is a heat-sink, the conduction mode is considered for contact thermal resistance and the natural convection mode for heat-sink thermal resistance. Joseph Fourier [3] defined the conduction mode of heat transfer as follows: *"the heat flux resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign,"* and we found that:

$$q = -k\frac{dT}{dx} \tag{3}$$

where

k is the thermal conductivity, W/m.K

T is the temperature, K

q is the heat rate per unit area and can be expressed as Q/A

A is an appropriate area, m^2

Equation (3) is known as Fourier's Law of heat conduction and thermal conductivity k is an intrinsic property of a homogeneous material which describes a material's ability to conduct heat. This property is independent of material size, shape or orientation. In one dimensional, we can write Fourier's Law in a simple scalar form as:

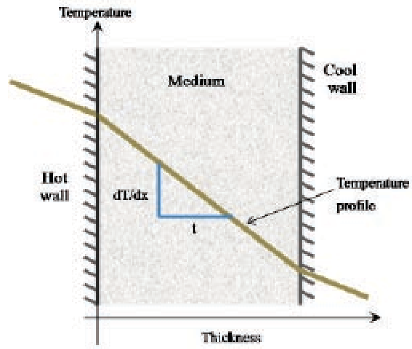

Figure 3 Heat conduction through a medium.

$$q = k\frac{\Delta T}{t} \tag{4}$$

where

t is the thickness of medium, m

q is the heat rate per unit area, W/m^2

When we use Equation (4), we are reminded that q and ΔT are both written as positive quantities and q *always* flows from a higher to lower temperature. Consider conduction from a hot wall to the cold side, as shown in Fig. 3 and from Fourier's Law, Equation (4) becomes :

$$Q = k\frac{A\Delta T}{t} \tag{5}$$

where

Q is heat quantities, W

A is the contact area of medium, m^2

According to the thermal circuit analysis and conduction theory of heat transfer, the thermal resistance (R_θ) of the medium in conduction mode of heat transfer is :

$$R_\theta = \frac{t}{kA} \quad {}^oC/W \tag{6}$$

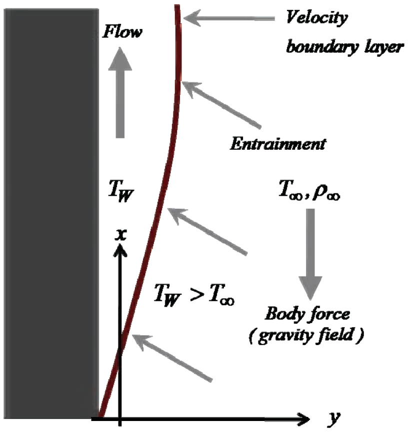

Figure 4 Natural convection flow over vertical surface.

The convection mode will be considered for cool air flowing past a warm body. In natural convection mode, fluid motion is induced by density differences resulting from the temperature gradients in the fluid as shown in Fig. 4 The heat transfer from the vertical surface can be expressed by Newton's Law of cooling, which gives the relationship between q and the different surface and ambien temperature, as [4]

$$q = \bar{h}A(T_W - T_\infty) \tag{7}$$

where

$\bar{h}$ is a convective heat transfer coefficient, W/m^2 ^{o}C

A is the total area of the vertical surface, m^2

From thermal circuit in the form of an electrical circuit comparison, the thermal resistance (R_θ) in convection mode of heat transfer is :

$$R_\theta = \frac{1}{\bar{h}A} \tag{8}$$

The R_θ in Equation (6) is referred to as the contact thermal resistance ($R_{\theta cs}$) and is referred to as the heat-sink thermal resistance ($R_{\theta sa}$) in Equation (8) .

3. Heat Pump Analysis for Power Semiconductors

Power losses or semiconductor power losses appear in the form of heat when they are in the saturate ON state or switching ON and OFF state. The heat must be transferred away from the junction to keep the junction temperature within the devices lower than the maximum ($T_{j(max)}$), as defined by the manufacturers, normally 150^{o}C. To avoid damaging the components, a heat-sink will be used to pump heat out of the devices. The heat transfer equation under steady state condition is [5] :

$$P_d = hA\Delta T \tag{9}$$

where

P_d is the rate transfer of the heat, W

A is the contact area of the medium, m^2

h is the heat transfer coefficient

ΔT is the temperature difference, K

A definition of thermal resistance is the ratio of temperature to power, thus thermal resistance (R_θ) becomes :

$$R_\theta = \frac{\Delta T}{P_d} \tag{10}$$

Fig.5 shows the heat dissipation and the thermal resistance of a single power semiconductor in still air without a heat-sink. Equations (9) and (10) indicate that the average heat dissipated from a junction to the case of the device component is given by :

$$P_d = \frac{T_{j(max)} - T_a}{R_{\theta ja}} \tag{11}$$

where $R_{\theta ja}$ is the thermal resistance from the junction to ambient, ^{o}C/W

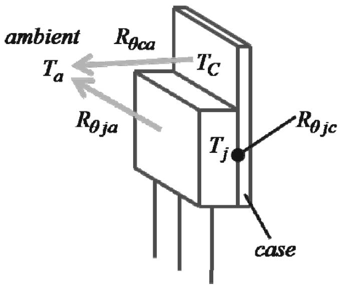

Figure 5 Heat flow of a device and its thermal resistance in still air.

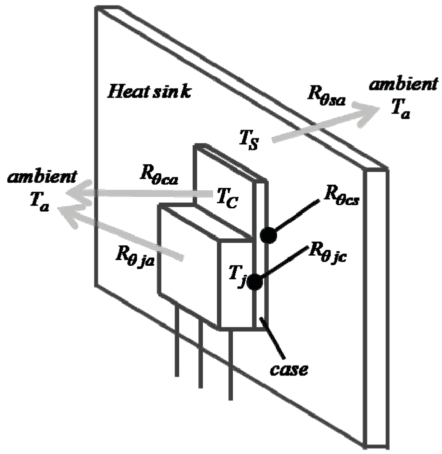

Figure 6 Temperature distribution on a power device with a flat plate heat-sink.

When a flat square plate heat-sink is used to manage the temperature on a power device, as shown in Fig.6, the thermal resistance is approximated by [5] :

$$R_{\theta sa} = \left(\frac{3.3}{\sqrt{\lambda w}} C_f^{0.25} \right) + \left(\frac{650}{A} C_f \right) \qquad K/W \quad (12)$$

where

λ is the thermal conductance of the heat-sink, W/K cm.

A is the contact area of the heat-sink (both sides), cm^2

w is the thickness of the heat-sink, mm.

C_f is the heat-sink orientation factor as in table 1

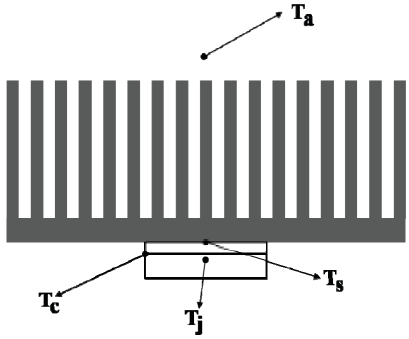

Figure 7 Temperature distribution of a power device.

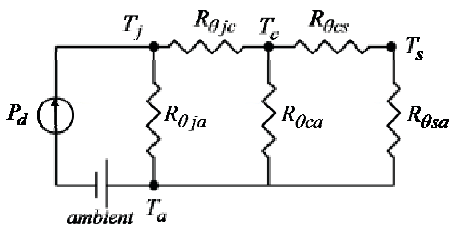

Figure 8 Thermal equivalent circuit of Fig.7.

Table 1 Heat-sink orientation factor

C_f	**Shiny**	**Blackened**
Vertical	0.85	0.43
Horizontal	1.00	0.50

Consider the temperature distribution of this power device when installed on a conventional heat-sink as, shown in Fig.7.

When the case of this power device is adjacent to the heat-sink, the contact thermal resistance must be taken into consideration. Contact thermal resistance has a relationship with the package type, interface flatness, mounting pressure and whether thermal conducting grease, then the thermal circuit turns as in Fig 8.

Junction-ambient thermal resistance ($R_{\theta ja}$) and case-ambient thermal resistance ($R_{\theta ja}$) are much

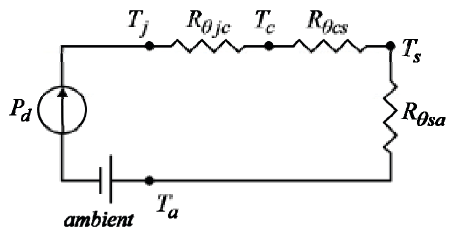

Figure 9 Thermal equivalent.

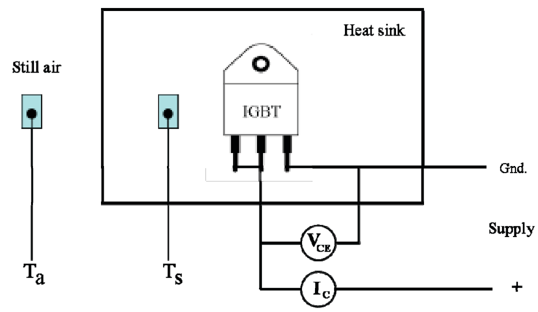

Figure 10 Physical setup for measuring $R_{\theta sa}$.

higher than another and are normally neglected when a heat-sink is used.

This condition creates the thermal equivalent circuit shown in Fig.9 and the thermal equation becomes :

$$\Delta T = P_d R_\theta \tag{13}$$

where

ΔT is the junction-ambient temperature, (T_j-T_a)

P_d is the power dissipation, W

R_θ is the thermal resistance from junction to ambient, °C/W

and can be written for the heat-sink to ambient thermal resistance ($R_{\theta sa}$) as

$$R_{\theta sa} = \frac{\Delta T}{P_d} - R_{\theta jc} - R_{\theta cs} \tag{14}$$

The relationship of $R_{\theta jc}$ and $R_{\theta cs}$ in terms of temperature and power dissipation can reduce Equation (14) to a simple form of $R_{\theta cs}$, or :

$$R_{\theta sa} = \frac{T_j - T_a}{P_d} - \frac{T_j - T_c}{P_d} - \frac{T_c - T_s}{P_d}$$

Then, the result is :

$$R_{\theta sa} = \frac{T_s - T_a}{P_d} \tag{15}$$

Equation (15) implies that we can find the thermal resistance of the heat-sink ($R_{\theta sa}$) with simple steps with a few variables involved. The following procedures demonstrate how to evaluate the thermal resistance of a heat-sink with the relationship in Equation (15).

4. A Practical Method for $R_{\theta sa}$ Measuring

Although, athere aer several ways to determine the thermal resistance of a heat-sink, most will operate in a nonlinear mode [6], [7]. This makes it difficult and complicated. This paper introduces a way to determine the $R_{\theta sa}$ of a heat-sink in a linear mode which is easier.

The method in Fig.10 demonstrates how to find the effective thermal resistance ($R_{\theta sa}$) of a heat-sink in a power circuit.

Initially, an IGBT will be mounted on the heat-sink, then a constant power is applied to the device and one waits for stability. In order to provide the system constants both heat-sink temperature and power dissipation, the IGBT must be operated in the linear mode; the gate is connected to the collector.

Since the power device is in linear mode, the total power dissipation is:

$$P_d = V_{CE} \times I_C \tag{16}$$

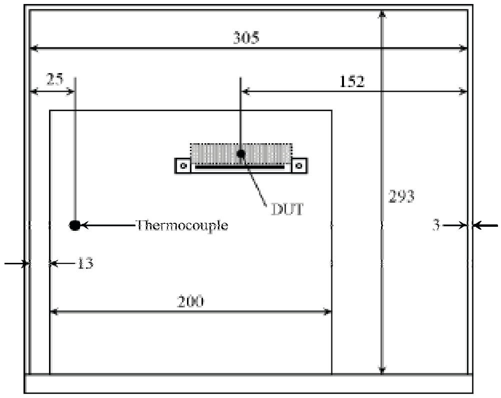

Figure 11 Test fixture support (mm.).

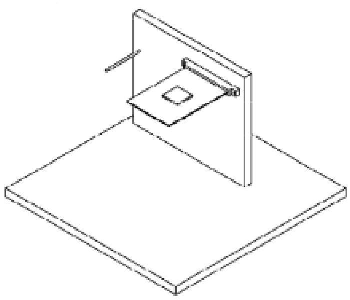

Figure 12 Test fixture support (cont'd).

For the greatest accuracy of the measurement, the environmental conditions will be under control [8]. The ambient temperature is measured away from the heat-sink under test in a steady-state (still-air) condition, based on the configuration of JEDEC 51-2A [9], as shown in Fig.11 and Fig.12. The temperature difference between the heat-sink (T_s) and ambient (T_a) in the steady state and the power dissipated from the IGBT (P_d) were used to determine the thermal resistance of a heat-sink ($R_{\theta sa}$), as described in Equation (15).

Table 2 summarizes the testing results, following the methodology of this paper.

Hence, the thermal resistance of this heat-sink ($R_{\theta sa}$) is equal to 1.24°C/W and 0.73°C/W for items 1 and 2 respectively.

Table 2 Testing results

Item	V_{CE} (V)	I_C (A)	P_d (W)	T_a (°C)	T_s (°C)
1	3.18	6.23	19.81	52.6	77.2
2	3.05	9.66	29.46	57.6	79.3

5. Conclusion

The theoretical and practical method mentioned above indicates a simple procedure to find the thermal resistance of the heat-sink ($R_{\theta sa}$), used in power circuits. With this simple step, we can eliminate the problem of heat-sinks appearing on the market with no crucial data for the designer. This method is very accurate if all major values are measured at the same time and under standard condition testing. We can utilize the standard condition from any standard agency such as the IEC, ASTM, JESD, etc. in order to set the physical testing to find the exact thermal resistance ($R_{\theta sa}$) of the heat-sink that we are using.

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