Thermal Characteristics of Optocouplers

INTRODUCTION

Behavior of any semiconductor device depends on the temperature of its die. Hence, electrical parameters are given at a specified temperature.

To sustain the performance of a component and to avoid failure, the temperature has to be limited by managing the heat transfer between the chip and the ambient atmosphere. It is a good design practice to make sure that the rated junction temperature of a phototriac optocoupler is not exceeded even if the device may not fall into what many designers consider the “power device” category. This is true for two main reasons.

The first is to increase the overall long-term reliability of the phototriac. The operating temperature of any solid-state device is inversely proportional to its long-term viability. Consequently, it is recommended to operate a device at the lowest practical operating junction temperature. Secondly, certain parameters are closely tied to the operating temperature of the device; these temperature-dependent parameters include, leakage current, trigger current, CTR, snapback voltage, and R_{ON}.

There are different ways of performing thermal calculations.

- Using a component thermal derating number
- Using a graph of allowable power versus temperature
- Using a thermal model

Use of a thermal derating number (given in power/degrees) is the simplest approach to take. Manufacturers are very conservative when deriving this number. Hence, this approach does not provide the most accurate results.

Use of a graph of allowable power versus temperature is very similar the first approach, but instead of a simple number, the designer follows a graph of allowable power versus temperature similar to the one in figure 1. Again, this is a very conservative approach and should allow for a very reliable design, but it does not provide the most accurate results.

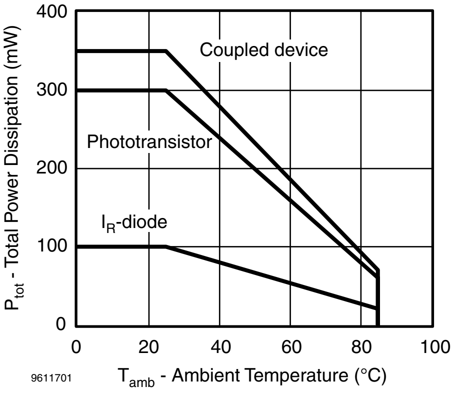

Fig. 1 - Allowable Dissipated Power

A more comprehensive of performing thermal calculation is to use a thermal model. Thermal models have been created for some Vishay optocouplers containing multiple dice, including phototriacs, to make these calculations as simple and as accurate as possible.

MULTIPLE DICE OPTOCOUPLER THERMAL MODEL

This document will demonstrate a simplified resistive model. When used correctly, this will give results that provide “engineering accuracy” for practical thermal calculations. The simplified electrical analogous model for any optocoupler is provided in figure 2.

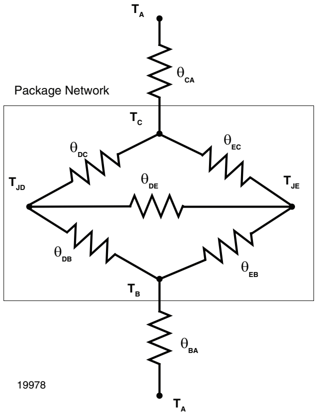

Fig. 2 - Multiple Dice Optocoupler Thermal Model/Resistor Network

Where:

θ_{CA} = Thermal resistance, case to ambient, external to the package
θ_{DC} = Thermal resistance, detector to case
θ_{EC} = Thermal resistance, emitter to case
θ_{DB} = Thermal resistance, detector junction to board
θ_{DE} = Thermal resistance, detector to emitter die
θ_{EB} = Thermal resistance, emitter junction to board
θ_{BA} = Thermal resistance, board to ambient, external to the package
T_{JE} = Emitter junction temperature
T_{JD} = Detector junction temperature
T_C = Case temperature (top center)
T_A = Ambient temperature
T_B = Board temperature

Thermal resistances and specified junction temperatures for a particular device are provided in select datasheets.

THERMAL ENERGY TRANSFER

There are three (3) mechanisms by which thermal energy (heat) is transported: conduction, radiation, and convection.

- Heat conduction is the transfer of heat from warm areas to cooler ones, and effectively occurs by diffusion.
- Heat radiation (as opposed to particle radiation) is the transfer of internal energy in the form of electromagnetic waves.
- Heat convection is the transfer of heat from a solid surface to a moving liquid or gas.

All three methods occur in optocouplers, but for most products, in most environments, the majority (~ 75 %) of heat leaving the package exits through the lead frame and into the board. This occurs because θ_{BA} is a conductive phenomenon with a much lower thermal resistance than the convective and radiative phenomena associated with θ_{CA} (θ_{CA} is typically an order of magnitude larger than other thermal resistances). Because very little heat leaves through the top of the package (heat convection), junction-to-case temperatures (θ_{DC} and θ_{EC}) can be eliminated as a consideration in most environments.

This is shown graphically in figures 3, 4, and 5 by the package temperature profile and strong heat flux contours evident in the die, lead frame, and board via. Because very little heat leaves through the top of the package, the top case temperature is a poor indicator of junction temperature.

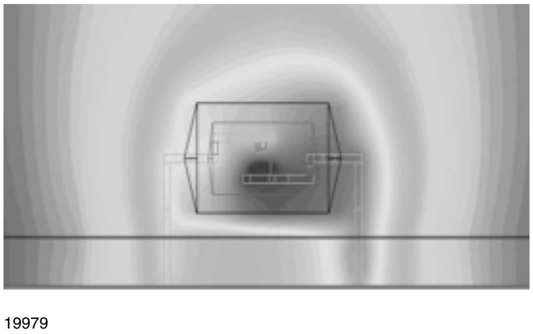

Fig. 3 - Example of Package Temperature Profile for 6 Pin DIP Phototriac

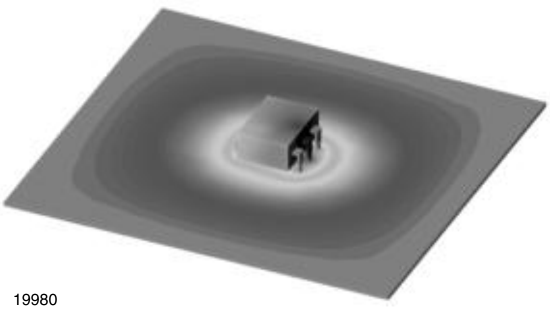

Fig. 4 - Example of Package Temperature Plot for 6 Pin DIP Phototriac

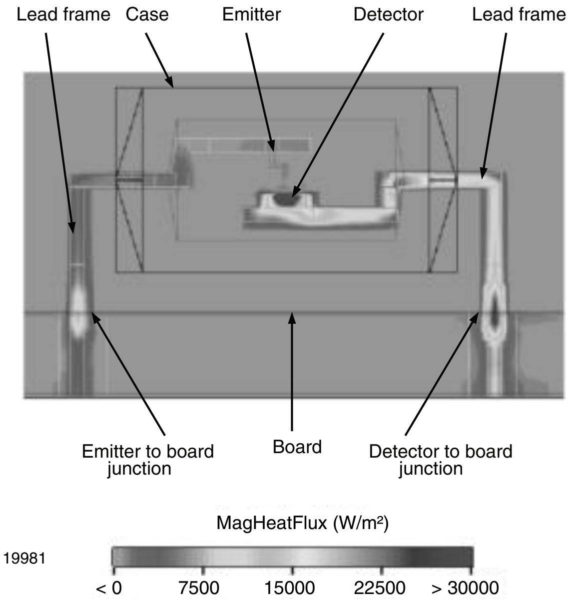

Fig. 5 - Example of Detector and Emitter Heat Flux for 6 Pin DIP Phototriac

This means that majority of the heat is transferred to the board, and very little heat is transferred to the air via the case. This can be verified in the thermal networks. Hence, θ_{DC} and θ_{EC} can be removed from the thermal model shown in figure 2. In this situation, the critical package thermal resistances become θ_{DE}, θ_{DB}, and θ_{EB}. θ_{BA} is the thermal resistance from the board to the ambient, and is primarily driven by the geometry and composition of the board. The type of board design used defines this characteristic.

When the junction-to-case thermal resistances are removed from consideration based on the assumption that very little heat leaves through the top of the package, the thermal model will be as illustrated in figure 6.

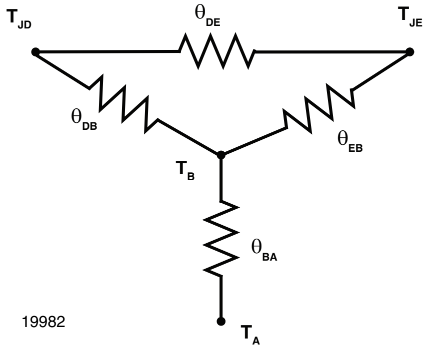

Fig. 6 - Simplified Multiple Dice Optocoupler Thermal Model/Resistor Network

THERMAL TO ELECTRICAL ANALOGY

The thermal-resistance characteristic defines the steady-state temperature difference between two points at a given rate of heat-energy transfer (dissipation) between the points. The thermal-resistance system is analogous to an electrical circuit where thermal resistance is equivalent to electrical resistance, temperature difference is equivalent to voltage difference, and rate of heat-energy transfer (dissipation) is equivalent to current, as shown in table 1.

TABLE 1 - ELECTRICAL PARAMETERS AND ITS EQUIVALENT THERMAL PARAMETERS

ELECTRICAL PARAMETER	THERMAL PARAMETER
R (Electrical resistance)	θ (Thermal resistance)
I (Electrical current)	P (Power dissipated)
V (Electrical voltage)	T (Temperature in °C)
R = V/I	$\theta = T/P$

In a thermal circuit, a constant current source represents power dissipation. This is because generated heat must flow (steady-state) regardless of the resistance in its path from higher temperature to lower temperature.

Assuming the power dissipated from the detector and the emitter (LED) are known (or estimated) and by measuring the board (and ambient) temperature, node temperatures can be calculated by solving the network equations. If it is desired to use the complete thermal resistance model, a more complex set of network equations will need to be solved.

This will enable the user to estimate at an early stage what the operating temperature(s) would be before the specific environment is known.

As an example, the analogous electrical model to calculate the temperature at both detector and emitter junctions given a set of thermal resistances at room temperature with 50 mW on the emitter (P_E) and 500 mW on the detector (P_D) is illustrated in figure 7.

In order to write equation to calculate the node temperatures, we will need to assume some heat flow direction. The selected heat flow directions are shown on figure 7.

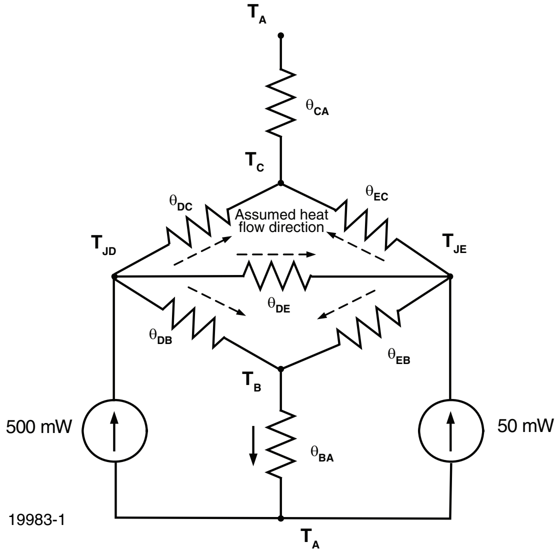

Fig. 7 - Complete Multiple Dice Optocoupler Thermal Model with Assumed Heat Flow Direction

Based on Figure 7, the following equations will need to be used to calculate the node temperatures.

$$- P_{DE} + P_{EB} + P_{EC} = P_E \quad (1)$$
$$P_{DE} + P_{DB} + P_{DC} = P_D \quad (2)$$
$$T_B - T_{JD} + \theta_{DB} \times P_{DB} = 0 \quad (3)$$
$$T_B - T_{JE} + \theta_{EB} \times P_{EB} = 0 \quad (4)$$
$$T_{JE} - T_{JD} + \theta_{DE} \times P_{DE} = 0 \quad (5)$$
$$T_B - \theta_{BA} \times (P_{EB} + P_{DB}) = T_A \quad (6)$$
$$T_C - \theta_{CA} \times (P_{EC} + P_{DC}) = T_A \quad (7)$$
$$T_C - T_{JD} + \theta_{DC} \times P_{DC} = 0 \quad (8)$$
$$T_C - T_{JE} + \theta_{EC} \times P_{EC} = 0 \quad (9)$$

Where:

P_{DB} = Power dissipation, detector junction to board
P_{DE} = Power dissipation, detector to emitter
P_{EB} = Power dissipation, emitter junction to board
P_{DC} = Power dissipation, detector junction to case
P_{EC} = Power dissipation, emitter junction to case

A simplified thermal circuit model is shown in figure 8.

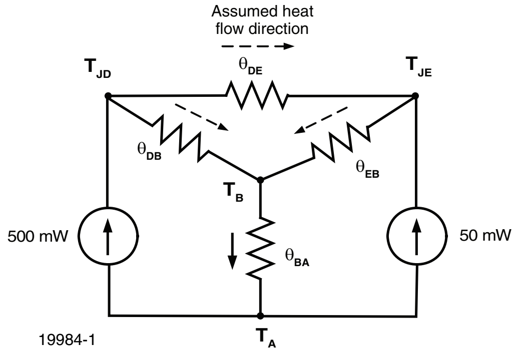

Fig. 8 - Simplified Thermal Model when T_A is known

When the simplified thermal model is used, equations 7 to 9 do not play any role in the node temperature calculation and equation 1 and 2 are simplified to equations 1’ and 2’. Since θ_{CA}, θ_{EC}, and θ_{DC} are not included in the simplified thermal model, all equations that include these resistances (equations 7 to 9) can be excluded for node temperature calculation.

When T_A is known, the following equations will need to be used to calculate the node temperatures:

$$- P_{DE} + P_{EB} = P_E \quad (1')$$

$$P_{DE} + P_{DB} = P_D \quad (2')$$

$$T_B - T_{JD} + \theta_{DB} \times P_{DB} = 0 \quad (3)$$

$$T_B - T_{JE} + \theta_{EB} \times P_{EB} = 0 \quad (4)$$

$$T_{JE} - T_{JD} + \theta_{DE} \times P_{DE} = 0 \quad (5)$$

$$T_B - \theta_{BA} \times (P_{EB} + P_{DB}) = T_A \quad (6)$$

On the other hand, for a desired T_B and/or when only T_B is known, Figure 8 is simplified to as shown in Figure 9.

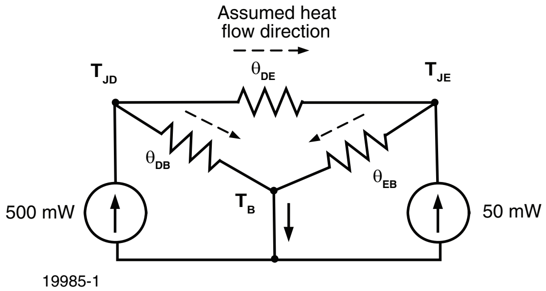

Fig. 9 - Simplified Thermal Model when only T_B is known

Please note that since T_B is given, θ_{BA} does not play any role in calculation node temperature. Hence the equation(s) that include θ_{BA} can be eliminated from list of equations required to calculated note temperatures.

Based on figures 8 and 9, the following equations will need to be used to calculate the node temperatures when only T_B is known:

$$- P_{DE} + P_{EB} = P_E \quad (1')$$

$$P_{DE} + P_{DB} = P_D \quad (2')$$

$$T_B - T_{JD} + \theta_{DB} \times P_{DB} = 0 \quad (3)$$

$$T_B - T_{JE} + \theta_{EB} \times P_{EB} = 0 \quad (4)$$

$$T_{JE} - T_{JD} + \theta_{DE} \times P_{DE} = 0 \quad (5)$$

Example 1:

Based on our characterization, the thermal resistances for a simplified 6 pin dip package optocoupler are derived/ measured to be as shown in table 2.

TABLE 2 - THERMAL RESISTANCE FOR VO30XX PHOTOTRIAC, SIMPLIFIED MODEL

THERMAL RESISTANCE	MOUNTED ON 2 LAYER BOARD	MOUNTED ON 4 LAYER BOARD
θ_{DE}	496 °C/W	496 °C/W
θ_{DB}	78 °C/W	78 °C/W
θ_{EB}	150 °C/W	150 °C/W
Typical θ_{BA}	72 °C/W	14 °C/W

It is important to note that the θ_{BA} is dependent upon the material, number of layers, and thickness of the board used. In our analysis, the optocouplers were mounted on 2 and 4 layer boards with a thickness of 4 mm. Obviously, the θ_{BA} for the two different boards were different as shown in table 2.

Using equations 1' and 2' and 3 to 6, plus the thermal resistances shown in table 2, and assuming emitter and detector power dissipation shown on figure 8, the node temperatures when T_A is known are calculated to be as shown in table 3.

TABLE 3 - CALCULATED NODE TEMPERATURE AND POWER WHEN T_A IS KNOWN FOR VO30XX PHOTOTRIAC IN 6 PIN DIP PACKAGE, P_D = 0.5 W, P_E = 0.05 W, T_A = 25 °C, SIMPLIFIED MODEL

CALCULATED VALUES	2 LAYER BOARD	4 LAYER BOARD
T_B (°C)	64.6	32.7
T_{JE} (°C)	78.6	46.7
T_{JD} (°C)	100	68.3
P_{DE} (W)	0.044	0.044
P_{EB} (W)	0.09	0.09
P_{DB} (W)	0.46	0.46

Example 2:

The designer can use the complete thermal model to calculated node temperatures. However, the results would not vary drastically from thermal calculation based on the simplified model for most products and in most environments. Hence, it is entirely up to the designer to decide how accurate and results must be for each individual design.

Table 4 provides all thermal resistances for package phototriacs in the 6 pin DIP.

TABLE 4 - COMPLETE THERMAL RESISTANCE FOR VO30XX PHOTOTRIAC

THERMAL RESISTANCE	MOUNTED ON 2 LAYER BOARD	MOUNTED ON 4 LAYER BOARD
θ_{DE}	496 °C/W	496 °C/W
θ_{DB}	78 °C/W	78 °C/W
θ_{EB}	150 °C/W	150 °C/W
θ_{EC}	139 °C/W	139 °C/W
θ_{DC}	103 °C/W	103 °C/W
θ_{CA}	3563 °C/W	3563 °C/W
Typical θ_{BA}	72 °C/W	14 °C/W

Using equations 1 to 9, the thermal resistances shown in table 4, and assuming emitter and detector power dissipation shown in figure 7, the node temperatures when T_A is known are calculated to be as shown in table 5.

TABLE 5 - CALCULATED NODE TEMPERATURE AND POWER WHEN TA IS KNOWN FOR COMPLETE THERMAL MODEL OF VO30XX PHOTOTRIAC IN 6 PIN DIP PACKAGE, P_D = 0.5 W, P_E = 0.05 W, T_A = 25 °C

CALCULATED VALUES	2 LAYER BOARD	4 LAYER BOARD
T_B (°C)	63.3	32.6
T_{JE} (°C)	81.9	51.6
T_{JD} (°C)	95.2	64.8
T_C (°C)	88.5	58.6
P_{DE} (W)	0.027	0.027
P_{EB} (W)	0.124	0.127
P_{DB} (W)	0.408	0.413
P_{DC} (W)	0.065	0.06
P_{EC} (W)	- 0.047	- 0.05

Regardless of the package size and type, the thermal analysis will need to be done to insure a solid design. Exceeding the thermal parameters can have detrimental and sometimes even disastrous consequences.