Thermal Models for Optocoupler Packages

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INTRODUCTION

Optimizing the design of electronics requires a careful selection of the electrical parameters, as well as paying attention to the thermal behavior of the components.

An understanding of the thermal characteristics of semiconductor devices is essential for their electrical performance and reliability. Therefore, thermal parameters should be defined for components in order to guide users towards maintaining safe operation. Exceeding temperature limits can lead to accelerated aging of the part along with degenerations in the internal structure, such as metal migrations, which will eventually drive the components into failure. Furthermore, various parameters are dependent on the operating temperature of the device, such as leakage current, CTR, R_{ON}, or snapback voltage.

Consequently, operation at low junction temperatures is recommended to extend the lifetime of the part.

BASICS OF HEAT TRANSFER

Heat transfer is the exchange of heat due to the temperature difference between systems. Under operation, the temperature within the semiconductor devices, more specifically at pn-junctions, will increase. The resulting heat will be transferred from the hot regions to the colder ones and this transfer can happen following three different mechanisms:

- Conduction
- Convection
- Radiation

Heat conduction, which happens regularly in nature, is the most common means of transfer. It occurs at the molecular level through the transfer of energy between atoms and molecules interacting with their neighbors.

Heat convection is the dominant means of transfer within liquids and gases. When a fluid (which can be air or liquid) is heated, the thermal energy causes the molecules to expand. As a result, the fluid loses density and rises to the top, forcing the cooler portion to the bottom.

Heat radiation is energy transfer via the emission of electromagnetic waves, which carry the energy away from the emitting object. Radiation is the only form of heat transfer in a vacuum. The amount of radiation is extremely non linear with the temperature of the emitting material.

Heat (thermal energy) can be added to a system, stored inside the system, and can leave the system. The amount of heat entering the system must be equal to the amount stored in or leaving the system:

heat generated = heat out

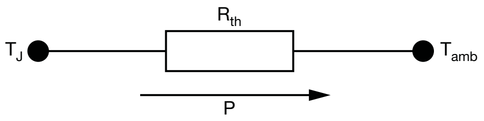

Fig. 1 - Junction to Ambient Resistor

$$P_J = P_{amb} = P \quad (1)$$

Thermal resistance:

$$\theta_{th} = \frac{\Delta T}{P} \quad (2)$$

$$P = \frac{T_J - T_{amb}}{\theta_{th}} = \frac{\Delta T}{\theta_{th}} \quad (3)$$

The next section describes how to establish a thermal model for application purposes.

THERMAL MODELS

Thermal energies can be handled using various methods:

- A thermal derating number to conduct thermal calculations
- A derating graph to help follow the course of allowable power over temperature to create a reliable design. However, it does not provide the most accurate results, which is in most cases not necessary since thermal considerations are extremely dependent on the actual situation

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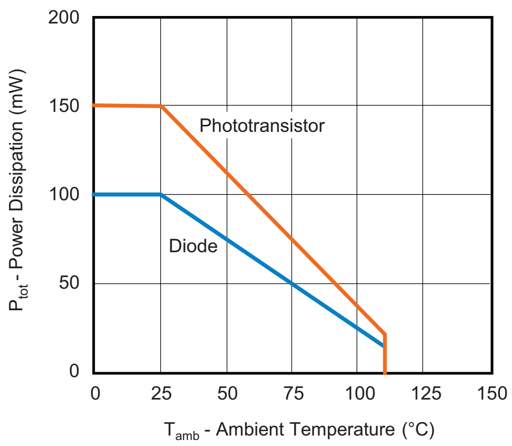

Fig. 2 - Power Dissipation vs. Ambient Temperature

- A thermal model based on thermal resistances to help map thermal energies and their flows in form of electrical systems. Models aim for the depiction of real world temperature distributions and heat flow using thermal resistances and thermal capacitors. The advantage of the thermal model is that the thermal system can be pictured as an electrical system, and thus the problem and its solutions are clearer

SUPERPOSITION MODEL

This application note concentrates on the superposition model, which is easy to generate and utilize and can be used to create the safety derating diagrams in datasheets.

This method models the contribution of e.g. two independent heat sources on a location, in case the total temperature is a linear superposition of these contributions.

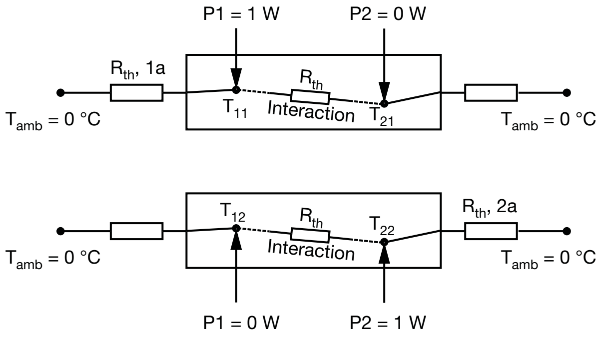

Fig. 3 - Paths of Heat

Temperature T_{11}, powered by node 1, can be converted to a true thermal resistance θ_{1a} since the direction of heat flow to thermal ground is known. The second temperature at node 2, T_{21}, helps generate the interaction resistance Ψ_{21}, where the direction is unknown.

When node 2 is also heated and measurements are taken, it will result in four temperature readings and the following equations:

$$\theta_{11} = \frac{(T_{11} - T_{amb})}{P_1} \tag{4}$$

$$\Psi_{12} = \frac{(T_{12} - T_{amb})}{P_2} \tag{5}$$

These equations can also be presented in a matrix form as follows:

$$\begin{pmatrix} \theta_{11} & \Psi_{12} \\ \Psi_{21} & \theta_{22} \end{pmatrix} \times \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \begin{pmatrix} T_1 - T_{amb} \\ T_2 - T_{amb} \end{pmatrix} \tag{6}$$

or

$$R \times P = \Delta T \tag{7}$$

When the model is extended with board and case nodes, the matrix will look as depicted below. However, the first two columns of the R matrix will be sufficient to calculate since the board and case are not powered but heated via unknown paths.

SUPERPOSITION MATRIX

For the following example, $P_e = P_d = 1$ W and the letters E, D, B, and C stand for emitter, detector, board, and case, respectively.

$$\begin{array}{c} \\ E \\ D \\ B \\ C \end{array} \begin{array}{c} \begin{array}{cccc} E & D & B & C \end{array} \\ \begin{pmatrix} \theta_{e,\ ja} & \Psi_{de} & \Psi_{be} & \Psi_{ce} \\ \Psi_{ed} & \theta_{d,\ ja} & \Psi_{bd} & \Psi_{cd} \\ \Psi_{eb} & \Psi_{db} & \theta_{ba} & \Psi_{cb} \\ \Psi_{ec} & \Psi_{dc} & \Psi_{bc} & \theta_{ca} \end{pmatrix} \end{array} \times \begin{pmatrix} P_e \\ P_d \\ NA \\ NA \end{pmatrix} = \begin{pmatrix} \Delta T_e \\ \Delta T_d \\ \Delta T_b \\ \Delta T_c \end{pmatrix} \tag{8}$$

Example:

Using thermal resistance values for $P_e = P_d = 1$ W of input power, one gets for instance the following results:

$$\begin{array}{c} \\ E \\ D \\ B \\ C \end{array} \begin{array}{c} \begin{array}{cccc} E & D & B & C \end{array} \\ \begin{pmatrix} 195 & 113 & 82 & 120 \\ 113 & 154 & 81 & 132 \\ 82 & 81 & NA & NA \\ 120 & 132 & NA & NA \end{pmatrix} \end{array} \times \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 308 \\ 267 \\ 163 \\ 253 \end{pmatrix} \tag{9}$$

SOLUTION OF THE MATRIX

$(\theta_{e,\ ja} \times P_e) + (\Psi_{de} \times P_d) + (\Psi_{eb} \times NA) + (\Psi_{ec} \times NA) = \Delta T_e$
$(195 \times 1) + (113 \times 1) + (82 \times 0) + (120 \times 0) = 308$

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MEASUREMENT METHODS FOR SUPERPOSITION MODEL

To achieve the input data to generate a superposition model, case and board temperatures are measured by thermocouples, whereas the junction temperatures, which cannot be easily measured, are simulated by a finite element method or computational fluid dynamics. For simulations, the material data is extracted from datasheets and 3D CAD models are used to detect the distance between the PCB and the bottom of the package. Furthermore, temperatures at emitter and detector junctions are simulated for a given input power.

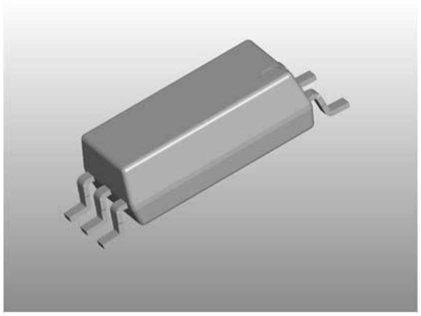

Fig. 4 - Example of a 3D Step File for LSOP Package

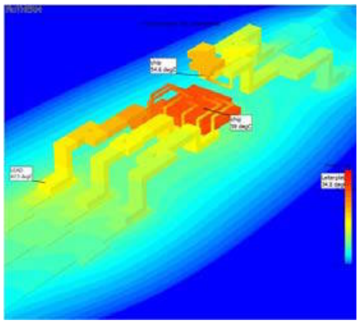

Fig. 5 - Example of Thermal Simulations

Following is an example of how the calculation is done:

Simulation

TEMPERATURES AT NODAL POINTS EXTRACTED FROM SIMULATION RESULTS WITH VOL3120 AT T_{amb} = 25 °C			
POWER NODE $P_{J, IN}$ / mW	EMITTER 50	DETECTOR 180	EMITTER AND DETECTOR 50 / 180
$T_{J, emitter}$ / °C	37.40	42.76	54.30
$T_{J, detector}$ / °C	30.19	54.46	59.02
$T_{case, peak}$ / °C	32.84	42.74	50.07
T_{board} / °C	28.58	39.11	42.22
T_{amb} / °C	25	25	25

The first two columns are generated by injecting a power of 50 mW to the emitter junction and subsequently 180 mW to the detector. To check on the model a third column is calculated by powering emitter and detector simultaneously.

Calculation Example

With the help of the formula (7), thermal resistances can be calculated:

$$R \times P = \Delta T$$

$$R = \frac{\Delta T}{P} = \frac{T_{j,\ emitter} - T_{amb}}{P_{j,\ emitter}} = \frac{37.40\ °C - 25\ °C}{0.05\ W} = 248\ K/W$$

THERMAL RESISTANCES CALCULATED WITH REFERENCE TO AMBIENT TEMPERATURE		
POWER NODE $P_{J, IN}$ / mW	EMITTER 50	DETECTOR 180
$R_{th, emitter}$ / K/W	248	99
$R_{th, detector}$ / K/W	104	164
$R_{th, board}$ / K/W	72	78

In matrix form for T_{amb} = 25 °C:

$$\begin{pmatrix} \theta_{e,\ ja} & \Psi_{de} & \Psi_{be} \\ \Psi_{ed} & \theta_{d,\ ja} & \Psi_{bd} \\ \Psi_{eb} & \Psi_{db} & \theta_{ba} \end{pmatrix} \times \begin{pmatrix} P_e \\ P_d \\ NA \end{pmatrix} = \begin{pmatrix} \Delta T_e + T_{amb} \\ \Delta T_d + T_{amb} \\ \Delta T_b + T_{amb} \end{pmatrix} \qquad (10)$$

Calculation vs. simulation

$$\begin{pmatrix} 248 & 104 & 72 \\ 99 & 164 & 78 \\ 72 & 78 & NA \end{pmatrix} \times \begin{pmatrix} 0.05 \\ 0.180 \\ 0 \end{pmatrix} = \begin{pmatrix} 55.2 \\ 59.7 \\ 42.6 \end{pmatrix} \text{ vs. } \begin{pmatrix} 54.3 \\ 59.0 \\ 42.2 \end{pmatrix} \qquad (11)$$

There is a 2 % variation between the calculation and simulation result of a device with emitter and detector powered at the same time.

Remove Case

The case thermal resistance will be neglected since temperature distribution over the surface varies. As per the model all power has to flow out of the board to the ambient, and compensation for the losses should be made at the board R_{th}. Emitter and detector thermal resistances are adjusted accordingly.

The thermal resistance from emitter and detector is computed in reference to the board temperature and not to the ambient temperature. Essentially this means splitting the R_{th} in portions such as emitter to board and board to ambient.

E.g: $R_{th,emitter}$ = (37.40 °C - 28.58 °C)/0.05 W = 176.4 K/W

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COMPUTED THERMAL RESISTANCES FROM EMITTER AND DETECTOR IN REFERENCE TO THE BOARD		
POWER NODE $P_{J, IN}$ / mW	**EMITTER 50**	**DETECTOR 180**
$R_{th, node,board}$ / K/W	176.4	85.3
$R_{th, board, amb}$ / K/W	71.6	78.4
$R_{th, node, amb}$ / K/W	248	164

The same procedure can be done for the interaction term:

COMPUTED THERMAL RESISTANCES FOR THE INTERACTION BETWEEN EMITTER AND DETECTOR		
POWER NODE $P_{J, IN}$ / mW	**EMITTER 50**	**DETECTOR 180**
$R_{th, interaction, board}$ / K/W	32.2	20.3
$R_{th, board, amb}$ / K/W	71.6	78.4
$R_{th, interaction, amb}$ / K/W	104	99

The board R_{th} will be adjusted to minimize the difference of temperature results from the model compared to the temperatures given by the simulation.

ADJUSTED THERMAL RESISTANCES TO MINIMIZE THE SIMULATION DIFFERENCE		
	EMITTER	**DETECTOR**
$R_{th, board}$ / K/W by results in	72 12 %	78 2 %
$R_{th, board, new}$ / K/W	63	77

ADJUSTED THERMAL RESISTANCES BY ADDING R_{th} OF NODE TO BOARD		
	EMITTER	**DETECTOR**
$R_{th, node, board}$ / K/W	176 + 63 = 239	85 + 77 = 162
$R_{th, off - axis}$ / K/W	32 + 63 = 95	20 + 77 = 97
Average $R_{th, off - axis}$ / K/W	96	96

The New Matrix

$$\begin{pmatrix} \theta_{e,\ ja} & \Psi_{de} & \Psi_{be} \\ \Psi_{ed} & \theta_{d,\ ja} & \Psi_{bd} \\ \Psi_{eb} & \Psi_{db} & \theta_{ba} \end{pmatrix} \times \begin{pmatrix} P_e \\ P_d \\ NA \end{pmatrix} = \begin{pmatrix} \Delta T_e + T_{amb} \\ \Delta T_d + T_{amb} \\ \Delta T_b + T_{amb} \end{pmatrix} \qquad (12)$$

Calculation vs. simulation

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0.05 \\ 0.180 \\ 0 \end{pmatrix} = \begin{pmatrix} 54.2 \\ 58.9 \\ 42 \end{pmatrix} \text{vs.} \begin{pmatrix} 54.3 \\ 59.0 \\ 42.2 \end{pmatrix} \qquad (13)$$

There is only a -0.5 % variation between the calculation and simulation.

DERATING DIAGRAMS

For the derating graph, the maximum junction temperature T_J is defined as 125 °C, power will be calculated not to exceed 125 °C. Ambient temperature is fixed to T_{amb} = 25 °C:

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0.05 \\ TBC \\ 0 \end{pmatrix} = \begin{pmatrix} ? \\ 125.0 \\ ? \end{pmatrix} \qquad (14)$$

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0.05 \\ 0.587 \\ 0 \end{pmatrix} = \begin{pmatrix} 93.4 \\ 125.0 \\ 73.2 \end{pmatrix} \qquad (15)$$

Below, the power dissipation is calculated where 125 °C is not exceeded with T_{amb} = 110 °C:

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0.033 \\ 0.073 \\ 0 \end{pmatrix} = \begin{pmatrix} 15.0 + 110 \\ 15.0 + 110 \\ 7.7 + 110 \end{pmatrix} = \begin{pmatrix} 125 \\ 125 \\ 117.7 \end{pmatrix} \qquad (16)$$

The point where derating for the detector starts is calculated as follows:

$$T_{derate} = T_{J,\ max.} - \frac{P_{diss,\ max.} \times (T_{J,\ max.} - T_{amb,\ 110})}{P_{diss,\ 110}} \qquad (17)$$

$$87.8\ °C = 125\ °C - \frac{0.180\ W \times (125\ °C - 110\ °C)}{0.073\ W} \qquad (18)$$

Repeating the same calculation for the emitter will let us generate the power derating graph:

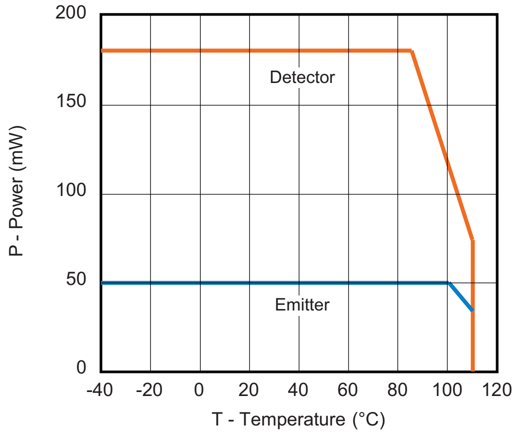

Fig. 6 - Example of a Derating Graph

Safety derating differs from power derating in the definition of the maximum temperature, where no power should be dissipated. While it was the temperature T_J max. = 125 °C for operating power derating, the critical temperature is T_S for safety derating, where the part is still capable of properly providing electrical isolation. For this reason, T_S is defined below the decomposition temperature at which the epoxy loses its properties. The coupler industry sets this safety temperature at T_S = 175 °C.

To determine the output safety power P_{SO}, the matrix calculations above will be conducted for T_{amb} = 25 °C:

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0 \\ 0.924 \\ 0 \end{pmatrix} = \begin{pmatrix} 89.0 + 25 \\ 150 + 25 \\ 71.2 + 25 \end{pmatrix} = \begin{pmatrix} 114 \\ 175 \\ 96 \end{pmatrix} \qquad (19)$$

To generate the safety diagram for the emitter, the maximum allowed current I_{SI} should be determined for T_S = 175 °C. If a maximum of V_f = 3 V is given:

$$\begin{pmatrix} 239 & 96 & 63 \\ 96 & 162 & 77 \\ 63 & 77 & NA \end{pmatrix} \times \begin{pmatrix} 0.627 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 150 + 25 \\ 60.3 + 25 \\ 39.5 + 25 \end{pmatrix} = \begin{pmatrix} 175 \\ 85 \\ 65 \end{pmatrix} \qquad (20)$$

Thus $I_{SI} = P_{SI}/3\ V$ = 209 mA or I_{SI} = 200 mA.

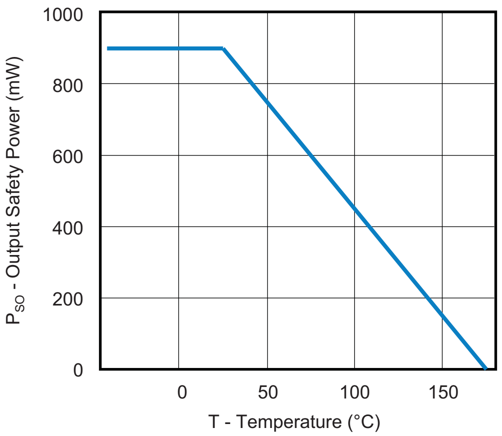

Fig. 7 - Example of a Safety Graph

THERMAL PARAMETERS FOR SSOP-4 PACKAGE

Simulation

TEMPERATURES AT NODAL POINTS EXTRACTED FROM SIMULATION WITH T_{amb} = 25 °C

POWER NODE $P_{J,\ IN}$/mW	**EMITTER 70**	**DETECTOR 150**
$T_{J,\ emitter}$ / °C	55.8	52.3
$T_{J,\ detector}$ / °C	38.9	75.2
$T_{case,\ peak}$ / °C	44.4	54.9
T_{board} / °C	39.4	56.7
T_{amb} / °C	25	25

Calculation Example

With the help of the formula (7), thermal resistances can be calculated:

$$R \times P = \Delta T$$

THERMAL RESISTANCES CALCULATED WITH REFERENCE TO SUPERPOSITION MODEL

POWER NODE $P_{J,\ IN}$/mW	**EMITTER 70**	**DETECTOR 150**
$R_{th,\ emitter}$ / K/W	440	197
$R_{th,\ detector}$ / K/W	197	335
$R_{th,\ case}$ / K/W	163	135
$R_{th,\ board}$ / K/W	235	123

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Derating Curves

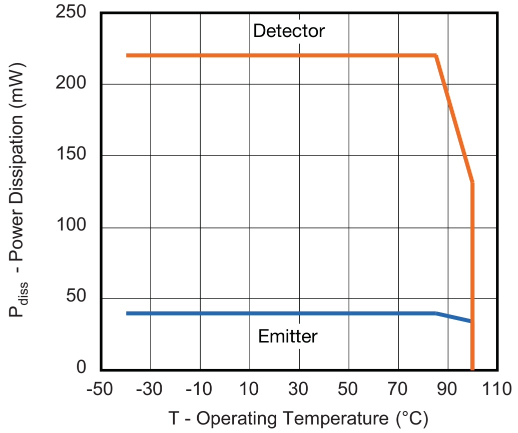

Fig. 8 - Power Derating Graph for SSOP-4 Package

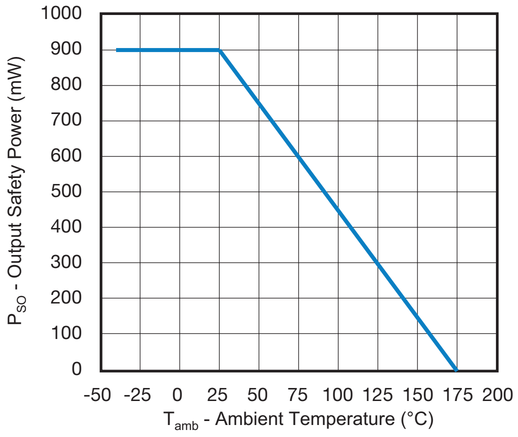

Fig. 9 - P_{SO} Derating Graph for SSOP-4 Package

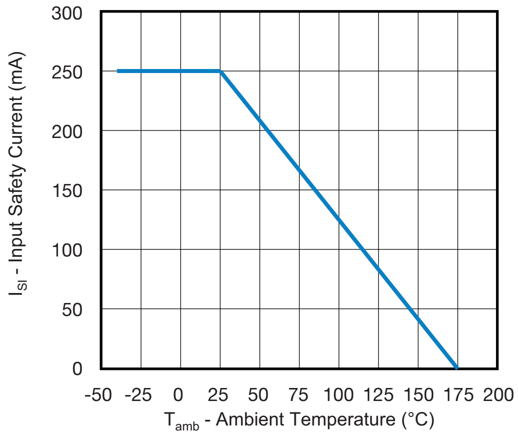

Fig. 10 - I_{SI} Derating Graph for SSOP-4 Package