Application Bulletin 210
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The successful design engineer has a clear understanding of the thermal impedance of the optical semiconductor. This understanding allows reliable system design that encompasses the dissipation rating of the optical semiconductor.

Introduction

The maximum power dissipation rating for a semiconductor device is usually defined as the largest amount of power which can be dissipated by the device without exceeding safe operating conditions. This quantity of power is a function of:

1. Ambient temperature
2. The maximum junction temperature considered safe for the particular device
3. The increase in junction temperature above ambient temperature per unit of power dissipation for the device package in a given mounting configuration

Item 3 is called thermal impedance and is determined in the lab with techniques such as those described in this bulletin. Item 2 is determined from reliability experiments and is usually considered to be 150°C, although it may be lower due to temperature limits imposed by the package material. Item 1 results in lower power dissipation ratings at higher ambient temperatures as described by derating curves, also described in this bulletin.

Thermal Impedance Calculations

The formula for calculating thermal impedance is

$$R_{THJA} = \frac{T_J - T_A}{P_D}$$

where: R_{THJA} = thermal impedance, junction to ambient (also called θ_{JA}); units are $\frac{^\circ C}{Watt}$

T_J = junction temperature of the device under test
T_A = ambient air temperature
P_D = device power dissipation

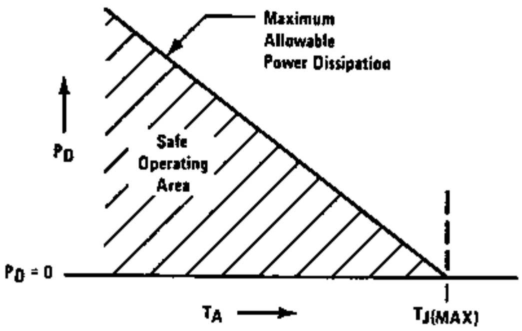
R_{THJA} refers to the thermal impedance of a device with no heat sink, suspended in still air on thermally non-conductive leads. This is the worst case (highest value) for thermal impedance.

To calculate the maximum allowable power dissipation, we substitute numbers for R_{THJA} (measured in the lab) and T_J (using the maximum value determined from reliability experiments) then rearrange terms to get

$$P_{D(MAX)} = \frac{T_{J(MAX)} - T_A}{R_{THJA}}$$

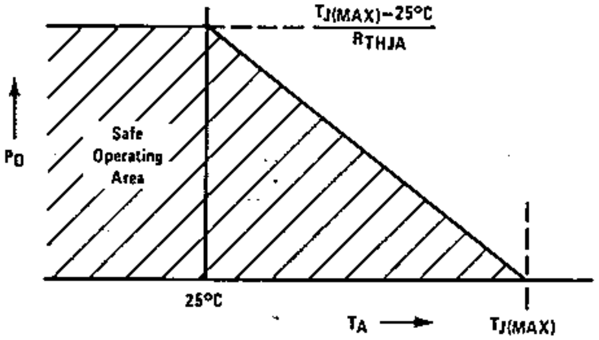
This results in a linear power dissipation rating curve which intercepts zero power dissipation at $T_A = T_{J(MAX)}$, and with a slope which is $-1/R_{THJA}$ as shown in Figure 1A:

Figure 1A. Initial Thermal Derating Curve



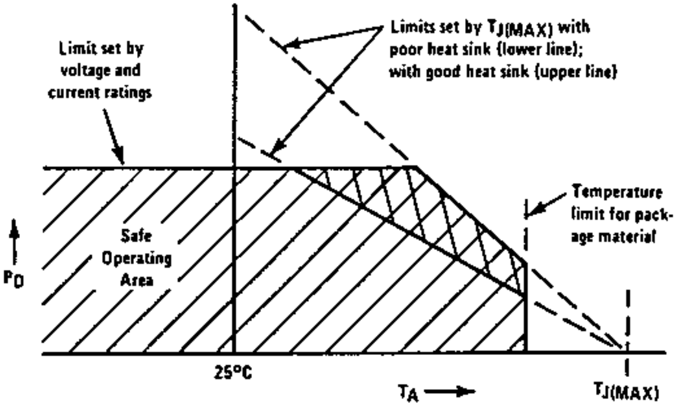
The usual (and conservative) method of rating power dissipation is to limit the curve to the safe value for normal room temperature, which is 25°C. The result is a curve shaped like Figure 1B:

Figure 1B. Thermal Operating Curve from 25°C



Since there are voltage, current, and ambient temperature limitations which are not related to chip temperature, the final power dissipation rating curve (often called a "derating" curve) for a given device might look like the curve shown in Figure 1C:

Figure 1C. Final Thermal Derating Curve



Since thermal impedance is very nearly constant for different levels of power dissipation, we merely have to measure the junction temperature at a known quantity of power dissipation, then substitute into the right side of the formula:

$$R_{THJA} = \frac{T_J - T_A}{P_D}$$

to find the thermal impedance of the device.

It is important to define the ambient conditions since air movement, lead length, and contact with thermal conductors all affect the measured T_J. The best case (lowest value) of thermal impedance is obtained with an infinite heat sink, i.e. by keeping the entire outside of the device at ambient temperature. Since case temperature equals ambient temperature under these conditions, infinite heat sink thermal impedance is called R_{THJC}, defined as:

$$R_{THJC} = \frac{T_J - T_C}{P_D}$$

where T_C = case temperature. The worst case encountered in real applications involves a device with full-length leads, mounted in a socket with no air movement. Thermal impedance under these conditions is called R_{THJX} and is calculated using the same formula as R_{THJA}. R_{THJX} is used to calculate actual worst case derating curves.

Junction Temperature Measurement

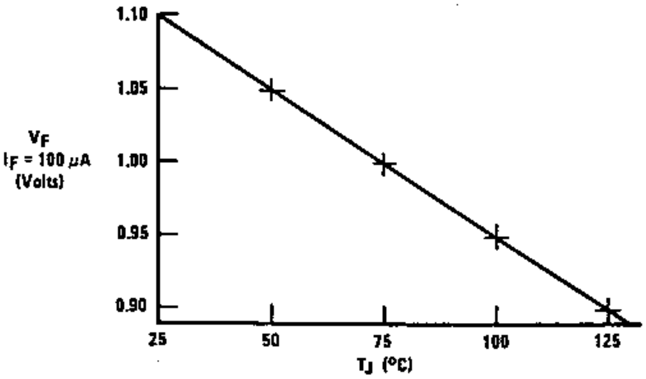
All these calculations depend on having a way to measure junction temperature in a chip while the device is dissipating power. This is done by using the chip as its own thermometer. Forward biased PN junctions have a voltage drop which decreases with temperature; by using a forward current small enough that no significant chip heating occurs, we can measure this voltage drop at known chip temperature simply by varying the ambient temperature of the package. Under these conditions, T_J approximately equals T_A, and we can control and measure T_A. See Table 1 for the junctions used for this measurement.

Table 1. Junctions Used for Measuring Temperature – T_J

Device Type	Junction Biased
LEDs, Diodes	Anode to Cathode
Transistors	Base-emitter or base-collector. If the device normally has no base lead as in phototransistors, special samples must be made with the base bonded out instead of the emitter.
ICs	Reverse bias the substrate (negative to V_{CC} lead, positive to ground).

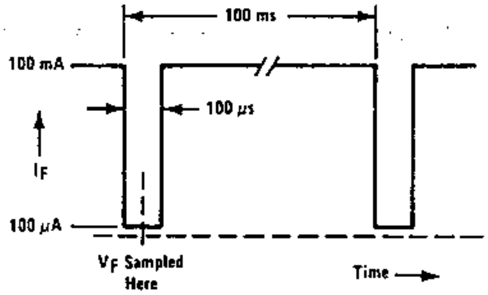
As a result of these measurements, we have a graphic representation of voltage drop versus junction temperature at a known low current. Figure 2A might be typical for an LED:

Figure 2A. Voltage Drop vs. Junction Temperature for IR LED



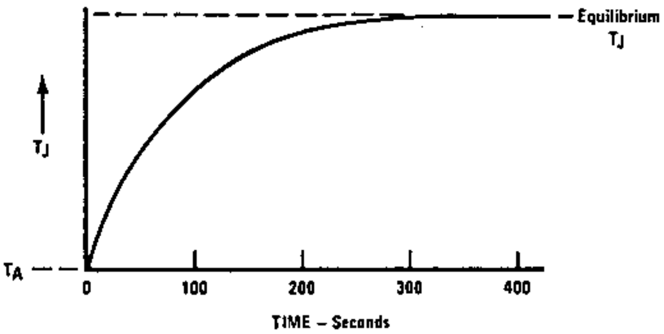
Now to find R_{THJA}, R_{THJX}, or R_{THJC} we place the device in the desired mounting configuration and apply a specific amount of power dissipation to the device, sufficient to provide significant chip heating. The junction temperature is monitored by interrupting the power and substituting the low forward bias current (our "thermometer"), 100 µA for the LED described in Figure 2A. The voltage drop must be measured before the junction has time to cool significantly. We use a 100 µs interruption which is consistent with the thermal time constant of the devices being measured; a sample and hold circuit maintains the reading so it can be recorded with a voltmeter. The applied waveform for the above LED would appear as shown in Figure 2B:

Figure 2B. Timing Cycle for Device Heating and Monitoring of Junction Temperature



Because of the sample and hold circuit, the voltmeter reading reflects the junction temperature of the chip as shown graphically in Figure 2A. For a typical plastic LED, the temperature rises after application of DC power for several minutes as shown in Figure 2C.

Figure 2C. Equilibrium of Junction Temperature



When the voltmeter reading has stopped changing, we (1) substitute the reading back into the graph to get the actual T_J; (2) multiply the large forward current, in this case 100 mA, by the voltage drop on the diode with 100 mA applied, to get the power dissipation; (3) measure the actual T_A; and (4) substitute into the R_{THJA} formula to get a value for thermal impedance.

Example

A typical OP290 infrared emitting diode is found to have V_F characteristics as shown at an I_F Of 100 μA:

T_A (°C)	V_F (Volts)
25	1.080
50	1.030
75	0.980
100	0.930

It is then connected to a test circuit and immersed in agitated silicone dielectric fluid at a temperature of 25°C; this is a good approximation of an infinite heat sink for a low power device. An I_F of 100 mA is applied. Every 100 ms the I_F is reduced to 100 μA for a period of 100 μs, after which the I_F returns to 100 mA. Using a sample and hold circuit we observe that the V_F of the device during the low current intervals starts out at 1.080 Volts but rapidly decreases, eventually stabilizing at 1.050 Volts. Interpolating between 1.080 Volts (25°C) and 1.030 Volts (50°C) we find that junction temperature is now 40°C.

The V_F is measured during the 100 mA I_F period and found to be 1.50 Volts. Thus, the power dissipation is 150 mW (99.9 percent of the time). Substituting into the formula,

$$R_{THJA} \text{ (infinite heat sink)} = R_{THJC} = \frac{40-25}{.150} = 100°\text{C/W}$$

When the same test is conducted with the device in still air, mounted in a PC board socket, the final values of V_F are 1.024 at 100 μA and 1.40 at 100 mA. Thus T_J = 53°C and

$$R_{THJX} = \frac{53-25}{.140} = 200°\text{C/W}$$

The power derating curves are:

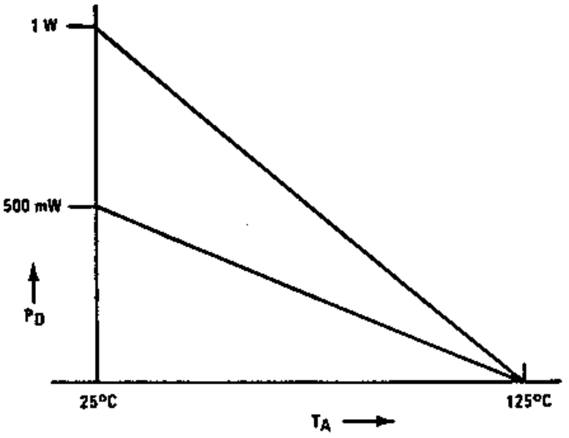
$$P_D = \frac{T_{J(MAX)} - T_X}{R_{THJA}} = \frac{125 - T_A}{100} \text{ with infinite heat sink, and}$$

$$P_D = \frac{125 - T_A}{200} \text{ with no heat sink.}$$

Martin McCrorey

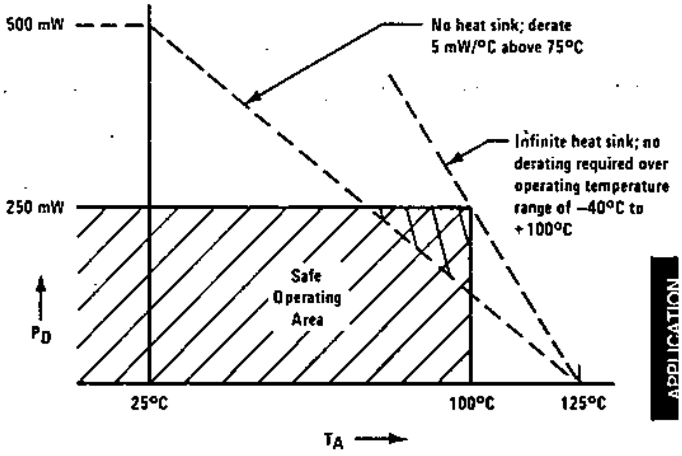
Graphing the derating curve gives two lines as shown in Figure 3A:

Figure 3A. Thermal Derating for "Infinite" and "No" Heat Sink



But the device is limited to 250 mW for reliability reasons, and the plastic package can withstand only 100°C due to the glass transistion temperature of the plastic. Thus, the final power derating curve is shown in Figure 3B:

Figure 3B. Final Thermal Derating



The entire shaded area can be used with an infinite heat sink; the cross-hatched area is forbidden for a device with no heat sink.

Conclusions

Power dissipation ratings for DC operating conditions are calculated with the techniques just described. For a device operated under steady state conditions, these procedures provide a method of establishing operating limits which are consistent with good device reliability. However, under pulsed conditions, the thermal time constants of the device must be considered. For information on the subject of junction heating under pulsed conditions, refer to Optek Application Bulletin 200, "Thermal Behavior of GaAs LEDs".