Thermal Behavior of GaAs LEDs

Application Bulletin 200

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Introduction

The output power (P_0) of a GaAs LED is a function of forward current (I_F). As this forward current increases, the output power will also increase. This forward current flowing through the LED generates heat (P_0) which causes the junction temperature (Θ_I) of the diode to increase. As the junction temperature increases, the output power decreases.

To obtain optimum operating conditions for a GaAs LED, the knowledge of the different thermal parameters and their influence on the major electro-optical parameters must be known. The purpose of this bulletin is to introduce these thermal parameters to the reader and provide a way to use them. Data will be presented and formulae will be given that will allow readers to determine if their system meets manufacturer's guidelines in both a DC mode and a pulsed mode.

Mathematical assumptions have been made to simply derivations and provide useful formulae in simple terms; empirical data has verified that the resulting error is less than 5%.

Care should be taken in making use of the information presented. For example: A current pulse could be short enough to cause no apparent problem within the presented material. However, it could be of sufficient magnitude and duration to exceed the allowable current density of the bond wire interconnect causing it to fail.

Thermal Parameters

The thermal behavior of a GaAs LED can be considered in a simple way by using the analogy of an electrical circuit. In this circuit, the heat power generator, the temperature differences, the thermal capacitors, and thermal resistors replace the conventional current or voltage generators, voltage differences, capacitors, and resistors respectively. Figure 1 shows this equivalent thermal circuit.

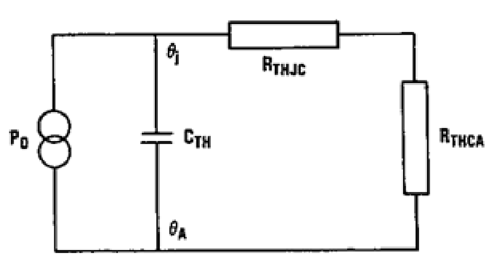

Table 1

Table 1
Thermal Parameters

Symbol	Parameter	Units
P_0	Output Power	W
P_D	Dissipated power	W
θ_j	Junction Temperature	°C
θ_A	Ambient Temperature	°C
C_{TH}	Thermal Capacitor	$Ws\,°C^{-1}$
R_{THJC}	Junction to Case Thermal Resistance	$°CW^{-1}$
R_{THCA}	Case to Ambient Air Thermal Resistance	$°CW^{-1}$
R_{THJA}	Junction to Ambient Air Thermal Resistance	$°CW^{-1}$
τ_{TH}	Thermal Time Constant ($R_{THJA} \times C_{TH}$)	s
K	Thermal Rating Factor	None
K_{eff}	Effective Duty cycle	None

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When forward current (I_F) flows through the GaAs LED, heat or power (P_0) is generated. Most of this heat is generated within:

(a) The upper section of the chip away from the mount area; the "N" area; the cathode.
(b) The mid section of the chip; the junction between the "N" and "P" regions.
(c) The lower section of the chip, the "P" area, the anode.

Heat is also generated in the contact interfaces and the conductors but this is considered negligible. This heat propagates through the chip and the mount surface primarily by thermal conduction. It is then transferred to the ambient air by thermal convection. All of the measurements and data presented in this bulletin were made with the air temperature in the room fairly constant throughout the test period and zero air velocity in the volume surrounding the device except for convection currents. Further, there were no extraneous thermal paths. Normal mounting of the devices in PC boards or adding heat sinks will improve the heat path. This is not considered in this bulletin with the exception of the last four (4) line items in Table 2. R_{THJA} should be considered as R_{THJX} in these cases. Table 2 lists several thermal parameters.

Table 2 - Thermal Parameters of Optek GaAs LEDs

GaAs LED Type	R_{THJA} (°CW^{-1})	C_{TH} (10^{-5}Ws °C^{-1})	τ_{TH} (10^{-2}s)	K
OP123/124, OP223/224	980	1.6	1.5	0.008
OP131-133(W), OP231-233(W)	490	3.0	1.5	0.008
OP140/240	740	4.3	2.0	0.008
OP160/260	740	5.3	3.9	0.008
OP290/295 C, B, A	188	1.4	0.3	0.008
OP291/296 C, B, A	188	1.4	0.3	0.008
OP292/297 C, B, A	188	1.4	0.3	0.008
OP293/298 C, B, A	500	4.0	1.5	0.008
OP8706 (LED)	700	5.2	3.6	0.008
OP123/124, OP223/224(1)	240	4.6	1.1	0.008
OP123/124, OP223/224(2)	400	4.5	1.8	0.008

(1) OP123/124 mounted on 0.062" double sided PC board.
(2) OP123/124 mounted in OPB125/253 housing.

The first four (OP123 through OP136) GaAs LED's are all hermetic packages. The maximum allowable junction temperature is 125°C. See the example below for one use of Table 2.

(1) OP123/124 has R_{THJA}—980°CW^{-1}
With ΔT_j—(125°C—25°C) - 100°C
The maximum power that can be dissipated is:

$$P_{D(max)} = \frac{\Delta T_j}{R_{THJA}} = \frac{100°C}{980°CW^{-1}} = 102 \text{ mW}$$

The next three of the units listed are plastic packages. The maximum allowable junction temperature is 85°C.
OP140 has R_{THJA}—740°CW^{-1}
With ΔT_j—(85°C—25°C) - 60°C
The maximum power that can dissipated is:

$$P_{D(max)} = \frac{\Delta T_j}{R_{THJA}} = \frac{60°C}{740°CW^{-1}} = 81 \text{ mW}$$

The derating factor above 25°C can be readily calculated from this information.

(2) OP123/124

$$\text{Derating Factor} = \frac{\Delta P_D}{\Delta T_j} = \frac{102 \text{ mW}}{100°C} = 1.02 \text{ mW°C}^{-1}$$

OP140

$$\text{Derating Factor} = \frac{81 \text{ mW}}{60°C} = 1.35 \text{ mW°C}^{-1}$$

Most manufacturers will give more conservative deratings than these numbers. This is normally due to the devices being used in a quasi heat sink. For example, the OP123/124 is normally mounted in a double sided PC board. The OP140 is normally soldered into a PC board. This would improve the R_{THJA} numbers. This becomes readily apparent by referring to the R_{THJA} number of 980°CW^{-1} for the OP123/124 in free air and the R_{TJHX} number of 240°CW^{-1} when the units are mounted in a double sided PC board as shown in Table 2 or the 400°CW^{-1} when they are mounted in the OPB700 or OPB701 housing. There is also a variation in R_{THJA} brought about by a variation in the integrity of the thermal bond between the GaAs LED and the mount surface. This is not easy to measure and is not adaptable to 100% production testing.

Temperature Response to a Thermal Power Step

A forward current step is introduced into a GaAs LED causing heat to be generated in the unit and causing the junction temperature to rise. This rise in junction temperature follows the formula shown below:

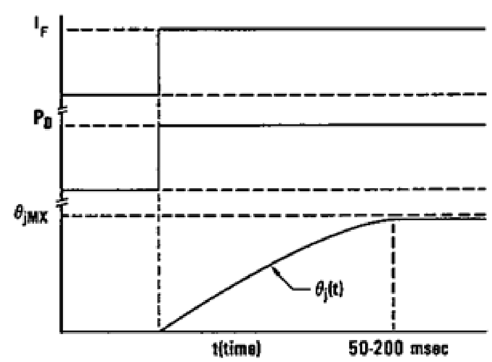
$$(3) \quad \theta_j(t) = \theta_A + P_D \times R_{THJA}\left(1 - e^{-\frac{t}{\tau_{TH}}}\right)$$

Where t is time in seconds
P_D is dissipated power
τ_{TH} is thermal time constant
R_{THJA} is junction to ambient air thermal resistance
θ_A is ambient temperature.

The junction temperature will approach its maximum value after t—5 or 5 thermal time constants which approximates 50 to 200 milliseconds. Figure 2 shows the forward current step, the resulting power generated within the chip itself, and the rise in junction temperature versus time.

Practically, P_0 will decrease slightly as soon as the junction temperature of the chip starts to rise and will stabilize 50 to 200 milliseconds after the power is applied. This is discussed in more detail in the section on power droop.

Figure 2—I_F, P_D, and Junction Temperature Versus Time



At temperature equilibrium, the maximum junction temperature (Θ_{jMX}) is:

$$(4) \quad \theta_{jMX} = \theta_A + P_D^{*} \times R_{THJA}$$

Where $P_D^{*} = V_F \times I_F$
V_F = Forward Voltage @ θ_{jMX}
θ_A = Ambient Temperature.

*For purpose of calculation, $P_D = P$ @ 25°C. The resulting error will have minor impact on the answer. Since V_F decreases with increasing temperature, the resulting answers will be conservative.

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Example: Using an OP133 which has a measured output of 5.3 mW @ Θ_A—25°C, calculated the output in a system where I_F—40 mA and Θ_A—50°C. The I_F versus P_0 without heating is relatively linear above 5 mA.

$$P_0 \text{ (40 mA @ 25°C)} = P_0 \text{ (100 mA)} \times 40/100 = 5.3 \text{ mW} \times 0.4 = 2.12 \text{ mW}$$

The power generated within the LED causing the junction temperature to rise is:

$$P_D = V_F \times I_F = 1.5 \text{ volts} \times 0.04\text{A} = 0.06 \text{ watts}$$

The final junction temperature is:

$$\theta_j = \theta_A + P_D R_{THJA} = 50°C + (0.06 \times 490) = 79.4°C$$

The output power of the OP133 is:

$$(5) \quad P_0(\theta_j) = P_0(25°C) \times e^{-K(\theta_j - 25°C)}$$

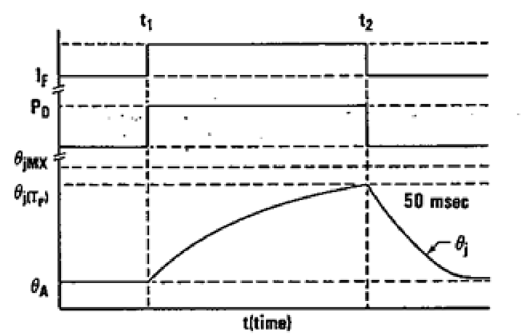
$$P_0(79.4°C) = 2.12 \times e^{-0.008(79.4 - 25)} = 1.38 \text{ mW}$$

This constitutes a 35% decrease in output power from the 25°C level. The value of K was taken from Table 2.

<u>Temperature Response to a Thermal Power Pulse</u>

A forward current pulse is introduced into a GaAs LED. This pulse is shorter than the 50 to 200 milliseconds required for the junction temperature to approach its highest value.

Figure 3—Current Pulse, Power Pulse, and $\theta_{j(T_p)}$ Versus Time



When I_F begins to flow, the power generated within the LED causes $\Theta_{j(t)}$ to follow the relationship:

$$(6) \quad \theta_{j(t)} = \theta_A + P_D R_{THJA}\left(1 - e^{-\frac{t}{\tau_{TH}}}\right) \qquad t_1 \le t \le t_2$$

When I_F stops @ time t_2, the P_0 will stop and the junction temperature Θ_j will start to decrease. This will follow the relationship:

$$(7) \quad \theta_{j(t)} = \theta_A + \left[P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)\right]\left(e^{-\frac{t}{\tau_{TH}}}\right) \qquad t > t_2$$

Example: A single 1A pulse 100 sec wide is applied to an OP136. What will the junction temperature be at the end of the 100 μsec pulse?

$$\theta_{jMX}(100\ \mu\text{sec}) = \theta_A + P_D R_{THJA}\left(1 - e^{-\frac{t}{\tau_{TH}}}\right)$$

$$\theta_{jMX}(100\ \mu\text{sec}) = 25°C + (2V \times 1A) \times 470\left(1 - e^{-\frac{10^{-4}}{2 \times 10^{-2}}}\right) = 25°C + 4.6°C = 29.6°C$$

Same as above except t = 1 msec

$$\theta_{jMX}(1\ \text{msec}) = 25°C + 2 \times 470\left(1 - e^{-\frac{10^{-3}}{2 \times 10^{-2}}}\right) = 25°C + 45.5°C = 70.5°C$$

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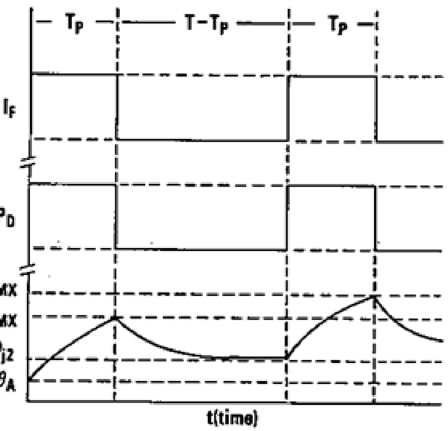
Temperature Response to Recurrent Thermal Pulses

A forward current pulse is introduced into a GaAs LED. At some later time, the pulse is repeated. Figure 4 shows the relationship of I_F to P_0 to Θ_j.

Figure 4—I_F, P_D, and θ_j Versus Time



The junction temperature Θ_j rises during the first power pulse from Θ_A to Θ_{j1MX}.

Refer to Equation (3).

$$\theta_{j1MX} = \theta_A + P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

The junction temperature Θ_j decreases during the off time of the power pulse from Θ_{j1MX} to Θ_{j2}.

Refer to Equation (7).

$$\theta_{j2} = \theta_A + \left[P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)\right]\left(e^{-\frac{(T - T_P)}{\tau_{TH}}}\right)$$

During the second pulse, the junction temperature will rise from Θ_{j2} to Θ_{j2MX}.

Refer to Equation (3), (6).

$$\theta_{j2MX} = \theta_{j2} + P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

After the second pulse is removed, the junction temperature will decrease to a new minimum temperature Θ_{j3}.

Refer to Equation (7).

$$\theta_{j3} = \left[\theta_{j2} + P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)\right]\left(e^{-\frac{(T - T_P)}{\tau_{TH}}}\right)$$

This swinging movement of Θ_j goes on and on with $\Theta_{jMX9n)}$ and $\Theta_{j(n)}$ gradually rising to a stabilized value. At the end of the n^{th} pulse, the junction temperature is Θ_{jn}MX.

$$(8) \quad \theta_{jnMX} = \theta_A + \left[P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)\right] \times \left[\sum_{i=0}^{i=n-1}\left(e^{-\frac{(T - T_P)}{\tau_{TH}}}\right)\right]$$

When the temperature stabilization point is finally reached, the Θ_{jMX} becomes:

$$(9) \quad \theta_{jMX} = \theta_A + P_D R_{THJA}\left(\frac{1 - e^{-\frac{T_P}{\tau_{TH}}}}{1 - e^{-\frac{T_P}{\tau_{TH}}\left(\frac{n}{1-n}\right)}}\right)$$

Where $n = \frac{T_P}{T}$ or duty cycle

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For small values of (n), the equation simplifies to:

$$(10)\quad \theta_{jMX} = \theta_A + P_D R_{THJA} K_{eff}$$

$$\text{Where } K_{eff} = \frac{1 - e^{-\frac{T_P}{\tau_{TH}}}}{1 - e^{-\frac{T_P}{n\tau_{TH}}}} = \text{effective duty cycle}$$

The minimum junction temperature becomes:

$$(11)\quad \theta_{jMIN} = \theta_A + P_D R_{THJA} K_{eff} \left(e^{-\frac{T_P}{n\tau_{TH}}} \right)$$

The delta temperature or the difference between Θ_{jMX} and Θ_{jMIN} becomes:

$$(12)\quad \Delta\theta_j = \theta_{jMX} - \theta_{jMIN}$$

$$\Delta\theta_j = P_D R_{THJA} K_{eff} \left(1 - e^{-\frac{T_P}{n\tau_{TH}}} \right)$$

$$= P_D R_{THJA} \left(1 - e^{-\frac{T_P}{\tau_{TH}}} \right)$$

Example: An OP136 is operated at I_F—1A, n—1%, T_P—100 μsec. What is Θ_{jMX}? Θ_{jMIN}? $\Delta\Theta_j$?

$$\text{OP136 } R_{THJA} = 470°CW^{-1}$$

$$P_D = 1A \times 2V = 2W$$

$$K_{eff} = \frac{1 - e^{-\frac{10^{-4}}{2 \times 10^{-2}}}}{1 - e^{-\frac{10^{-4}}{2 \times 10^{-4}}}} = 1.26 \times 10^{-2}$$

Refer to Equation (10).

$$\theta_{jMX} = 25°C + (2 \times 470 \times 1.26 \times 10^{-2}) = 36.7°C$$

Refer to Equation (11).

$$\theta_{jMIN} = 25°C + (2 \times 470 \times 1.26 \times 10^{-2}) \left(e^{-\frac{10^{-4}}{2 \times 10^{-4}}} \right) = 32.1°C$$

Refer to Equation (12).

$$\Delta\theta_j = 36.7° - 32.1 = 4.6°C$$

Verifying, refer to Equation (12).

$$\Delta\theta_j = 2 \times 470 \left(1 - e^{-\frac{10^{-4}}{2 \times 10^{-2}}} \right) = 4.6°C$$

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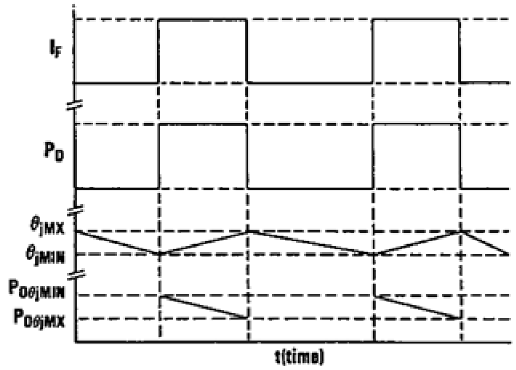
Power Droop

The junction temperature of an LED will oscillate between Θ_{jMX} and Θ_{jMIN} under recurrent pulses after the pulses have been on for a period of time. The radiant power output (P_0) will decrease during the "ON" time as the junction temperature rises from Θ_{jMIN} to Θ_{jMX}. This is shown in Figure 5 and is called power droop.

Figure 5— I_F, P_D, and θ_j, and P_0 Versus Time



This decrease in power out or power droop during the "ON" cycle is dependent on Θ_{jMX} and Θ_{jMIN}. Most systems desire this droop to be kept below 5-10% in order to limit the influence on system operation. The major factors that control this are the forward current (I_F), forward voltage drop (V_F), pulse duration (T_p), duty cycle (n), and thermal resistance (R_{THJA}).

$$P_0(\theta_{jMIN}) = P_0(25°C) \times e^{-K(\theta_{jMIN} - 25°C)}$$

$$P_0(\theta_{jMX}) = P_0(25°C) \times e^{-K(\theta_{jMX} - 25°C)}$$

By definition, the power droop is:

$$P_{Droop} = \frac{P_0(\theta_{jMIN}) - P_0(\theta_{jMX})}{P_0(\theta_{jMIN})}$$

$$(13) \quad P_{Droop} = 1 - e^{-K(\theta_{jMX} - \theta_{jMIN})}$$

Example: An OP136 is being operated at I_F—1A and n—1%. What is the maximum pulse width for a droop of 5%?

$$P_{Droop} = 1 - e^{-K(\theta_{jMX} - \theta_{jMIN})}$$

$$0.05 = 1 - e^{-0.008(\theta_{jMX} - \theta_{jMIN})}$$

$$\theta_{jMX} - \theta_{jMIN} = 6.41°C$$

Refer to Equation (12) for $\Delta\theta_j$.

$$\Delta\theta_j = P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

$$6.41 = 2 \times 470\left(1 - e^{-\frac{T_P}{2 \times 10^{-2}}}\right)$$

$$T_P = 138\ \mu sec$$

Example: What is the power droop if T_P is changed to 100 μsec?

$$\Delta\theta_j = P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

$$= 2 \times 470\left(1 - e^{-\frac{10^{-4}}{2 \times 10^{-2}}}\right)$$

$$= 4.6°C$$

$$P_{Droop} = 1 - e^{-0.008(4.5°C)}$$

$$= 3.6\%$$

Example: What is the power drop on the OP133 under the same conditions as the OP136?

$$I_F = 1A,\ n = 1\%,\ T_P = 100\ \mu sec$$

$$\Delta\theta_j = P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

$$= (1A \times 2.5\ V) \times 490\left(1 - e^{-\frac{10^{-4}}{1.5 \times 10^{-2}}}\right)$$

$$= 8.07$$

$$P_{Droop} = 1 - e^{-0.008(8.07)}$$

$$P_{Droop} = 0.0625 = 6.25\%$$

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Example: What is the maximum power that can be dissipated in the OPB950 when T_P is 20 μsec, duty cycle is 1%, and droop is restricted to 5% maximum?

$$P_{Droop} = 1 - e^{-K(\theta_{jMX} - \theta_{jMIN})}$$

$$0.05 = 1 - e^{-0.008(\theta_{jMX} - \theta_{jMIN})}$$

$$(\theta_{jMX} - \theta_{jMIN}) = 6.41°C$$

$$\Delta\theta_j = P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

$$6.41 = P_D \times 250\left(1 - e^{-\frac{20 \times 10^{-6}}{3.24 \times 10^{-3}}}\right)$$

$$P_D = 4.23$$

With a V_F of approximately 2.5 volts, the maximum I_F under the above conditions would be 1.7 amps.

Conclusion

The data presented will allow calculations that effect various power levels, pulse widths, and duty cycles on Optek GaAs LEDs. All standard products are covered. The pertinent thermal formulae are included as a separate section for easy reference. These formulae coupled with the information given in Table 2 will allow designers to optimize their design utilizing Optek LEDs in the pulse mode.

Daniel Cognard

William Nunley

8. Thermal Formulae

1. Maximum Power Dissipation

$$P_{D(MAX)} = \frac{T_j}{R_{THJA}}$$

2. Derating Factor

$$\frac{\Delta P_D}{\Delta T_j}$$

3. Effective Duty Cycle (Square current pulses)

$$K_{eff} = \frac{1 - e^{-\frac{T_P}{\tau_{TH}}}}{1 - e^{-\frac{T_P}{n\tau_{TH}}}}$$

4. Maximum Junction Temperature (Repetitive Pulses)

$$\theta_{jMX} = \theta_A + P_D R_{THJA} K_{eff}$$

5. Minimum Junction Temperature (Repetitive Pulses)

$$\theta_{jMIN} = \theta_A + P_D R_{THJA} K_{eff}\left(e^{-\frac{T_P}{n\tau_{TH}}}\right)$$

6. Junction Temperature Swing

$$\Delta\theta_j = P_D R_{THJA}\left(1 - e^{-\frac{T_P}{\tau_{TH}}}\right)$$

7. Power Droop

$$P_{Droop} = 1 - e^{-0.008(\Delta\theta_j)}$$

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