Application Note

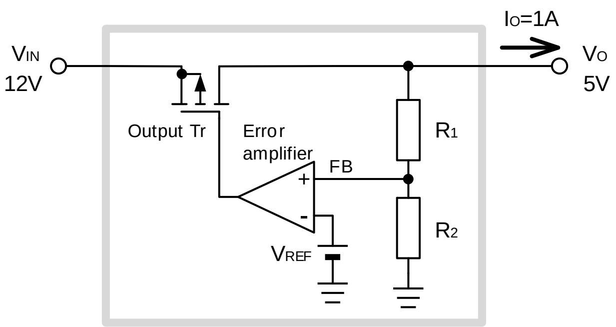
Linear Regulators

Thermal Design for Three-Terminal Voltage Regulators

No.16020EAY20

Three terminal regulators provide a simple, effective, and stable solution to power voltage regulation requirements. Some applications, however, require special techniques to deal with concerns about overheating. Lack of thorough consideration for thermal design may result in poor efficiency of the IC and shorter lives of semiconductors. This application note is a design guide for 3-terminal regulators used in combination with the TO220CP-3 package and a heatsink.

An input voltage range of 7.5-25 V and output current of 1 A can be found on the datasheet of a 5 V output regulator that belongs to the 78XX family of 3-terminal voltage regulators (Rohm model designation: BA78xx and BA178xx). If the regulator is configured to a 12 V input voltage and 1 A output current, for example, the calculation gives about 7 W of power dissipation (see Figure 1).



$$P = (V_{IN} - V_O) \times I_O + (V_{IN} \times I_{CC}) \quad [W]$$
$$= (12-5) \times 1 + (12 \times 4.5m) = 7.054 \ [W]$$

Where:

I_{CC} = Current consumption of the IC [A]

Figure 1 Power Dissipation

Configuration without Heatsink

The datasheet provides information on the thermal resistance of the TO220CP-3 package, based on which junction temperature can be calculated. Figure 2 shows a thermal equivalent circuit model without a heatsink, which gives Equation (1) for the junction temperature calculation. The junction temperature T_J at the ambient temperature of 25°C is determined as follows.

$$T_J = \theta_{JA} \times P + T_A \quad [°C] \qquad (1)$$
$$= 62.5 \times 7 + 25°C = 462.5 \ [°C]$$

Where:

θ_{JA} = Thermal resistance between the IC junction and ambient temperature [°C/W]

P = Power loss of the IC [°C]

T_A = Ambient temperature [°C]

The calculation proves that this configuration does not work since the maximum junction temperature rating is 150°C. Be sure to check the maximum rating of the junction temperature of the IC to be used on its datasheet because different ICs have maximum junction temperatures of their own.

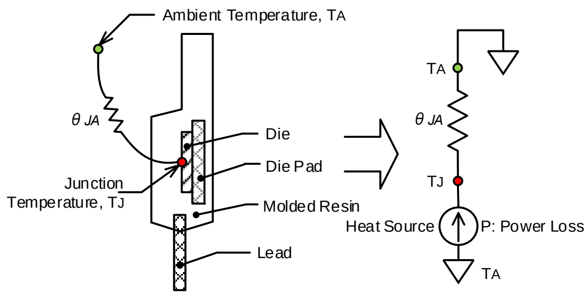


Figure 2 Thermal Equivalent Circuit Model

Now, do the arithmetic to determine up to how much output current the circuit withstands if no heatsink is used. A maximum junction temperature rating of 150°C allows it to work for some time, however the behavior reliability is significantly sacrificed. It is commonly known that the junction temperature should be kept within 80% of its maximum rating for better circuit reliability. Another well-known fact is that the life of a device halves and the failure rate doubles per 10°C increase in the junction temperature. Therefore, circuits should be designed to operate at as low of a junction temperature as possible to reduce the failure rate.

Parameters:
Input voltage, $V_{IN} = 12\ [V]$
Output voltage, $V_O = 5\ [V]$
Maximum ambient temperature, $T_{Amax} = 60\ [°C]$
Maximum junction temperature, $T_{Jmax} = 120\ [°C]$
(80 % of rating)
Thermal resistance, $\theta_{JA} = 62.5\ [°C/W]$
(Available from the datasheet)

$$P = \frac{T_{Jmax} - T_{Amax}}{\theta_{JA}} = \frac{120 - 60}{62.5} = 0.96\ \ [W] \qquad (2)$$

$$I_O = \frac{P}{V_{IN} - V_O} = \frac{0.96}{12 - 5} = 0.137\ \ [A] \qquad (3)$$

The calculation above proves that only 0.137 A of current are allowed per 1 A capacity, if no heatsink is used for the circuit.

Configuration with Heatsink

A heatsink mounted on an IC reduces thermal resistance. It achieves a lower junction temperature, which translates into efficient use of the IC. Figure 3 shows a thermal equivalent circuit model with a heatsink.

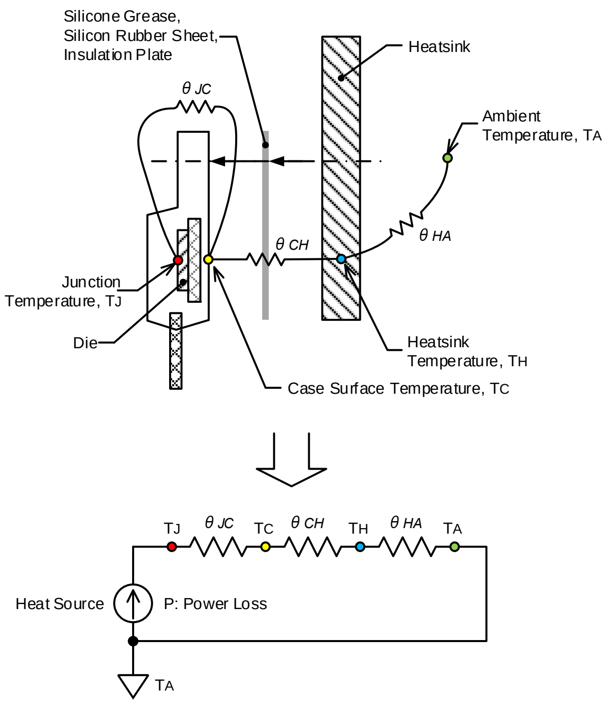


Figure 3 Thermal Equivalent Circuit Model

Junction-to-case thermal resistance, θ_{JC}

The power loss P of the IC serves as the heat source that contributes to the increase in temperature at the die junction T_J. The TO220CP-3 package is designed to be fitted with a heatsink screwed to the back of the case. Heat from the die (junction temperature T_J) is transferred to the back surface of the case (case surface temperature T_C). The thermal resistance during this heat transfer is expressed as θ_{JC}, which can be obtained from the datasheet.

Contact thermal resistance, θ_{CH}

The thermal resistance in the region between the back of the case (case surface temperature T_C) and the heatsink (heatsink temperature T_H) is expressed as θ_{CH}, which represents the contact thermal resistance of the case and the heatsink. Flatness, contact area, and tightening strength are the factors that largely affect the contact thermal resistance at the case-to-heatsink interface. The variation in the thermal resistance becomes large if the heatsink is directly mounted onto the case surface without silicone grease at the expense of stability in flatness and contact area. The use of silicone grease or other suitable media applied to the contact surface is strongly recommended to secure stable and low thermal resistance.

Thermal resistance specific to silicone grease or silicone rubber sheet is available from the manufacturers. An approximate thermal resistance can be calculated using the specification value in product catalogs as follows.

The typical thermal resistance of a silicone grease falls within a range of 1 to 6 W/m･K, which can be usually referenced in a product catalog. Substitute the value for the silicone grease into the following equation.

$$\theta = \frac{t}{K \times L \times W} \quad [°C/W] \qquad (4)$$

Where:
t = Silicone grease thickness $[m]$
K = Thermal conductivity $[W/m \cdot K]$
L = Length of the contact surface of the case $[m]$
W = Width of the contact surface of the case $[m]$

Example calculation
Parameters (Make sure each unit is correct.):
Silicone grease thickness, $t = 0.1\ [mm]$
Thermal conductivity, $K = 1\ [W/m \cdot K]$
Length of the contact surface of TO220CP, $L = 15\ [mm]$
(Available from the datasheet)
Width of the contact surface of TO220CP, $W = 10\ [mm]$
(Available from the datasheet)

$$\theta = \frac{t}{K \times L \times W} = \frac{\frac{0.1}{1000}}{1 \times \frac{15}{1000} \times \frac{10}{1000}} = 0.67\ [°C/W] \quad (5)$$

Some of the calculated thermal resistances for different thicknesses of silicone grease are shown in Table 1, which indicates that thicker, uneven application of silicone grease contributes to an increase in the thermal resistance.

Thermal Conductivity (*W/m・K*)	Thermal Resistance (°*C/W*)		
	t = 0.1 mm	*t* = 0.2 mm	*t* = 0.3 mm
1 - 6	0.11 - 0.67	0.22 - 1.33	0.33 - 2.0

Table 1 Silicone Grease Thickness and Thermal Resistance

Mica insulation plates are common material for case-to-heatsink insulation, however Rohm's TO220CP-3 package (Figure 4), which has the entire surface coated in molded resin, has no metal parts exposed on the back, eliminating the need for an insulation plate.

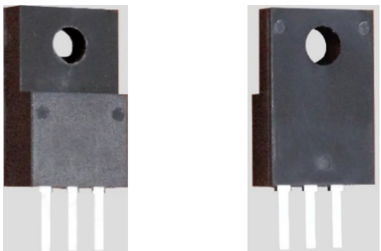


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Figure 4 Rohm's TO220CP-3 Package

Thermal resistance of heatsink, θ_{HA}

The total thermal resistance from the heatsink to the ambient air is expressed as θ_{HA}, and involves calculating the difference in the heat flow from the heatsink temperature T_H to the ambient temperature T_A. For the sake of practicableness, the calculation uses actual measurements, since heatsink thermal resistance shows characteristics similar to a distribution constant that is not easily expressed in a formula. The specific thermal resistances of heatsinks are available from the manufacturers.

Below is the calculation of thermal resistance θ_{HA} required for the equivalent circuit model shown in Figure 3. Equations (6) and (7) are led for the equivalent circuit.

$$T_J = (\theta_{JC} + \theta_{CH} + \theta_{HA}) \times P + T_A \quad [°C] \quad (6)$$

$$\theta_{HA} = \frac{T_J - T_A}{P} - \theta_{JC} - \theta_{CH} \quad [°C/W] \quad (7)$$

$$= \frac{T_J - T_A}{(V_{IN} - V_O) \times I_O + (V_{IN} \times I_{CC})} - \theta_{JC} - \theta_{CH} \quad [°C/W] \quad (8)$$

Where:

$\theta_{HA} =$ Thermal resistance of the heatsink $[°C/W]$
$\theta_{JC} =$ Junction − to − Case thermal resistance $[°C/W]$
$\theta_{CH} =$ Contact thermal resistance of silicone grease $[°C]$
$T_J =$ Junction temperature $[°C]$
$T_A =$ Ambient temperature $[°C]$
$V_{IN} =$ Input voltage $[V]$
$V_O =$ Output voltage $[V]$
$I_O =$ Output current $[A]$
$I_{CC} =$ Current consumption of the IC $[A]$

Here, we use the same parameters as the previous section.

Parameters:

Input voltage, V_{IN}
Output voltage, V_O
Output current, I_O
Current consumption of the IC, I_{CC}
(Available from the datasheet)
Ambient temperature, $T_A = 60$ [°C]
Junction temperature, $T_J = 120$ [°C] (80 % of rating)
Thermal resistance, $\theta_{JC} = 5.7$ [°C/W]
(Available from the datasheet)
Thermal resistance, $\theta_{CH} = 0.3$ [°C/W]
(Available from the manufacture)

When the parameters are substituted into Equation (8), we get the following.

$$\theta_{HA} = \frac{120 - 60}{(12 - 5) \times 0.5 + (12 \times 4.5m)} - 5.7 - 0.3 = 10.9 \quad [°C/W]$$

From the manufacturer's heatsink catalog, select a heatsink that has a thermal resistance no greater than the calculated 10.9°C/W. Without a heatsink, up to 0.137 A current was allowed per 1 A. Now, with a suitable heatsink, the allowable current increased to 0.5 A. Consider reducing the input voltage or output current if the calculated value is small, zero, or negative, as this indicates that the target junction temperature cannot be reached even when a heatsink is in use.

Precautions for Heatsink Mounting

- A minimum of 0.05 mm flatness is required for the mounting surface, including burrs and sagging at holes for mounting screws. Insufficient flatness may result in damage to the case or die, and poor adhesion between the case and the heatsink.

- Lower the contact thermal resistance by applying silicone grease from the IC case to the heatsink interface or putting a silicone rubber sheet in-between them.

- Heads of tightening screws must be round, pan, truss, binding, or flat.

- DO NOT use self-tapping screws. Tightening torque may exceed the allowable maximum.

- DO NOT use countersunk screws. They allow excess stress to be applied to the device.

- Fasten screws at the specified tightening torque to ensure sufficient heat dissipation effect. Insufficient contact between the case and heatsink increases the contact thermal resistance. Applying a torque higher than specified may result in damage to the IC. Use a torque screwdriver that assures torque is set within the optimum range.

Package	Tightening Torque [*N*・*m*]
TO220CP-3	0.4 - 0.6

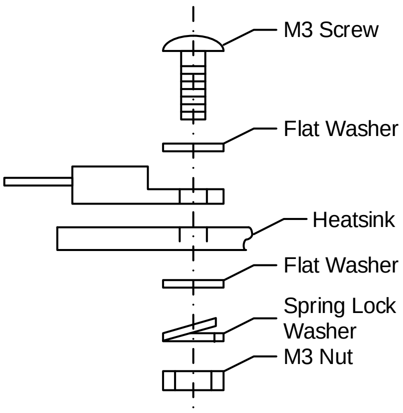

Figure 5 Heatsink Mount Structure

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