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Application Report

SLVA462–May 2011

Understanding Thermal Dissipation and Design of a Heatsink

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ABSTRACT

Power dissipation performance must be well understood prior to integrating devices on a printed-circuit board (PCB) to ensure that any given device is operated within its defined temperature limits. When a device is running, it consumes electrical energy that is transformed into heat. Most of the heat is typically generated by switching devices like MOSFETs, ICs, etc. This application report discusses the thermal dissipation terminology and how to design a proper heatsink for a given dissipation limit.

Thermal Dissipation

The maximum allowable junction temperature (T_{JMAX}) is one of the key factors that limit the power dissipation capability of a device. T_{JMAX} is defined by the manufacturer and usually depends on the reliability of the die used in the manufacturing process.

The typical equation used for calculation of the dissipation is shown in Equation 2:

$$\theta_{JA} = \frac{T_J - T_A}{P_D} \qquad (1)$$

Where:

θ_{JA} = thermal resistance
T_J = junction temperature
T_A = ambient temperature
P_D = power dissipation

To discover the maximum power that the device can dissipate, rearrange Equation 2 to:

$$P_{DMAX} = \frac{T_{JMAX} - T_A}{\theta_{JA}} \qquad (2)$$

With the help of θ_{JA} and T_{JMAX}, which are mentioned in the TPS54325 data sheet (SLVS932), P_{DMAX} is calculated. For example, in the data sheet, θ_{JA} is mentioned at 44.5°C/W and T_{JMAX} is given as 125°C. Using this at different ambient conditions of 25°C and 85°C, one can arrive at the values mentioned in the data sheet of 2.25 W and 0.9 W, respectively. A parameter called derating factor can be derived from this. The derating factor is linear, so if the dissipation is 2250 mW for a 100°C rise (from 25°C to 125°C), for each one degree increase in ambient temperature, the power dissipation rating has to be decreased 2250/100 = 22.50 mW/°C. This parameter is sometimes used for calculation, when the power dissipation values are unspecified.

In a specific synchronous buck converter application where the input is 5 V and output is 2.5 V at 1 A, 2.5 W is delivered to the load. Note that this is not the power dissipated in the device. When no specific efficiency curves are in a data sheet for the application, an assumption of the efficiency is to be considered (90%) to calculate the input power. So, the input power in this case is approximately 2.5/0.9 = 2.75 W, and the power dissipation in the converter is approximately 2.75 – 2.5 = 0.25 W. Some of this power is dissipated in the inductor, which is external to the chipset. Because the DCR can be known from the inductor data sheet, the inductor power is:

$P_{inductor} = I_{out2} \times DCR = 1^2 \times 100 \times 10^{-3} = 100$ mW.

The device power dissipation is now 250 mW - 100 mW = 150 mW, and the junction temperature rise above ambient is calculated using the formula:

$(\theta_{JA} \times P_D) + T_A = T_J$

$T_J = 75 \times 0.15 + T_A = 11.25°C$ above ambient (75°C/W is the thermal resistance taken as a example)

Consider another example of calculating the dissipation of a logic device SN74ACT240. Based on the data sheet specifications of the device and actual operating conditions, power dissipated by the logic can be estimated as per the preceding equations. The device power dissipation consists of two basic components – the unloaded power dissipation inherent to the device and the load power dissipation, which is a function of the device loading.

$P_{D(total)} = P_{D(unloaded)} + P_{D(loaded)}$

Power dissipation in an unloaded logic device can be calculated using the following equations:

$P_{D(unloaded)} = V_{CC} \times I_C$

$I_C = I_{CC} + I_{input} + I_{dynamic}$

Where:

V_{CC} = supply voltage
I_{CC} = quiescent current
I_{input} = total current when inputs are high
$I_{dynamic}$ = power supply current per unit frequency

$I_{input} = I_I \times N_I \times D_I$ and $I_{dynamic} = C_{pd} \times V_{cc}$

Where:

I_I = supply current for a high input
N_I = number of inputs on high level
D_I = duty cycle of inputs at high level
C_{pd} = power dissipation capacitance

The loading of a logic device can significantly effect the power dissipation. Most of the logic loads appear to be capacitive, leading to more of dynamic power dissipation. Typical load capacitance is approximately 10 pF to 20 pF. Power dissipation in a loaded logic device can be calculated using the following equations:

$P_{D(loaded)} = V_{OH} \times N_O \times f \times C_L$

Where:

V_{OH} = logic high output voltage
N_O = number of outputs loaded with CL
f = output switching frequency
C_L = load capacitance per output

Heatsink Design

θ_{JA} is actually made up of at least two separate thermal resistances in series. One is the thermal resistance inside the device package, between the junction and its outside case, called θ_{JC}. The other is the resistance between the case and the ambient, θ_{CA} . Because θ_{JC} is under the control of the manufacturer, nothing can be done with it. It is typically low. Another stage can be introduced between the case and ambient. This is where the heatsink in θ_{CA} is now split into θ_{CS} and θ_{SA}, where θ_S is the thermal resistance of the interface compound used, and θ_{SA} is the thermal resistance of the heatsink. The equation is now:

$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$$

$$\frac{T_J - T_A}{P_D} = \theta_{JC} + \theta_{CS} + \theta_{SA} \quad (3)$$

Rearranging this:

$$\theta_{SA} = \frac{T_J - T_A}{P_D} - \theta_{JC} - \theta_{CS} \quad (4)$$

In most cases, the T_J, P_D, and θ_{JC} are given in the device manufacturer's data sheet; θ_{CS} and T_A are used as defined parameters. The ambient air temperature T_A for cooling the devices depends on the operating environment in which the component is expected to be used. Typically, it ranges from 35°C to 45°C, if the external airflow through a fan is used and from 50°C to 60°C, if the component is enclosed. The interface resistance θ_{CS} depends mainly on the interface material and its thickness and also on the surface finish, flatness, applied mounting pressure, and contact area. Reliable data can be obtained directly from material manufacturers.

With all the parameters defined, θ_{SA} becomes the required maximum thermal resistance of a heatsink for the application. In other words, the thermal resistance value of a chosen heatsink for the application has to be equal to or less than the previous θ_{SA} value for the junction temperature to be maintained at or below that specified .

The following are the various important parameters in selecting a heatsink.

1. Thermal resistance θ_{SA}
2. Airflow
3. Volumetric resistance
4. Fin density
5. Fin spacing
6. Width
7. Length

The thermal resistance is one parameter that changes dynamically depending on the airflow available. Airflow is typically measured in linear feet per minute (LFM) or CFM (cubic feet per minute). LFM is a measure of velocity, whereas CFM is a measure of volume. Typically, fan manufacturers use CFM because fans are rated according to the quantity of air it can move. Velocity (speed) is more meaningful for heat removal at the board level, which is why the derating curves provided by most power converter manufacturers use this. Typically, airflow is either classified as natural or forced convection. Natural convection is a condition with no external induced flow and heat transfer depends on the air surrounding the heatsink. The effect of radiation heat transfer is very important in natural convection, as it can be responsible for approximately 25% of the total heat dissipation. Unless the component is facing a hotter surface nearby, it is imperative to have the heatsink surfaces painted to enhance radiation. Forced convection occurs when the flow of air is induced by mechanical means, usually a fan or blower.

Limited thermal budget and space make the choice of a particular type of heatsink very important. This is where the volume of the heatsink becomes relevant. The volume of a heatsink for a given flow condition can be obtained by using the following equation:

$$\text{Volume}_{(\text{heatsink})} = \text{volumetric resistance (Cm}^3\ ^\circ\text{C/W)/thermal resistance } \theta_{SA}\ (^\circ\text{C/W})$$

An approximate range of volumetric resistance is given in the following table:

Available Airflow (LFM)	Volumetric Resistance (Cm^3 °C/W)
NC	500 – 800
200	150 - 250
500	80 - 150
1000	50 - 80

The next important criterion for the performance of a heatsink is the width. It is linearly proportional to the performance of the heatsink in the direction perpendicular to the airflow. Considering an example, an increase in the width of a heatsink by a factor of two, three, or four increase the heat dissipation capability by a factor of two, three, or four. Similarly, the square root of the fin length used is approximately proportional to the performance of the heatsink in the direction parallel to the airflow. In case of an increase in the length of the heatsink by a factor of two, three, or four only increases the heat dissipation capability by a factor of 1.4, 1.7, or 2.

If the board has sufficient space, it is always beneficial to increase the width of a heatsink rather than the length of the heatsink. This is only the beginning of an iterative process before the correct and the actual heatsink design is achieved.

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