LM3886 Cooling Notes

(Prepared by DNi for the discussion in the thread **LM3886 Thermal Experiment (with data)** in diyAudio.com)

1. Short introduction to the theory of one-dimensional steady-state heat conduction

Given a solid wall whose sides are exposed to different (constant) temperatures, heat will be transferred from the warmer to the colder side of the wall by the physical mechanism known as conduction. This heat transfer mode is characteristic of solid materials, and is also possible in gases in liquids, but to a much lesser extent because temperature difference in fluids spontaneously leads to flow, and the resulting heat transfer mechanism is referred to as convection.

The quantity of heat transferred through the wall per unit time is calculated by the following formula:

$$q = k \cdot A \cdot \frac{\Delta T}{h} \qquad (1)$$

where
q - the quantity heat transferred per unit time, i.e. the thermal power $[W]$,
k – thermal conductivity of the wall material $\left[\frac{W}{m \cdot K}\right]$,
A – wall area $[m^2]$,
ΔT – temperature difference $[K]$,
h - wall thickness in the direction of heat flow $[m]$.
Note the use of Kelvin $[K]$ instead of [℃] as the unit for temperature difference in the SI system.

For a given physical situation, the wall material and geometry are fixed, and the equation can be expressed as:

$$q = K \cdot \Delta T, \quad \text{with } K = \frac{k \cdot A}{h} \qquad (2)$$

where K may be termed thermal conductance of the wall, with units of $\left[\frac{W}{K}\right]$. Its reciprocal value is referred to as thermal resistance, i.e.

$$R_{th} = \frac{h}{k \cdot A} \qquad (3)$$

with units of $\left[\frac{K}{W}\right]$. The quantity of heat transferred is then:

$$q = \frac{\Delta T}{R_{th}} \qquad (4)$$

or, the other way around, the temperature difference needed to achieve a given heat transfer rate with a given R_{th}:

$$\Delta T = q \cdot R_{th} \qquad (5)$$

Note the analogy with the Ohm's law in that temperature difference is analogous to the potential difference, thermal resistance to the Ohm's resistance, and the heat transfer rate to the electrical current.

If one is dealing with a multi-layer, i.e. sandwiched wall, whereby thermal resistances of the individual layers are different, the resultant thermal resistance is calculated as a sum of the thermal resistances of the individual layers, i.e.

$$R_{th} = R_{th,1} + R_{th,2} + \cdots + R_{th,n} \qquad (6)$$

whereas the resultant thermal conductance of a sandwich wall is calculated in the same way as the parallel connection of multiple resistors:

$$K_{th} = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \cdots + \frac{1}{K_n}} \qquad (7)$$

Note that thermal resistance contains the geometry data of the heat transfer assembly, and is thus valid only for the particular assembly it has been established for.

2. LM3886 heat transfer estimates

Thermal resistance of the LM3886 plastic package is quoted by TI at approx. 2 K/W, almost as a side-line in their AN-1192 Application Report (the reliability of this information will be dealt with in some detail in a separate section further below), whereas the one of the T package is 1 K/W. These data will be used for the calculations presented below.

Since from the standpoint of heat transfer the only difference between the two packages is the epoxy layer at the back of the plastic package, one can use the difference between the two thermal resistances in order to determine thermal conductivity of the epoxy compound used. Therefore, with:
$R_{th,e} = 1\ [K/W]$ - thermal resistance of the epoxy layer,
$h_e = 0.5\ [mm]$ – epoxy layer thickness, and
$A = 20 \cdot 19.5 - 0.5 \cdot 3.05^2 = 385\ [mm^2]$ – heat transfer area at the back of the package, we have:

$$k_e = \frac{h_e}{R_{th,e} \cdot A} = 1.3\ \left[\frac{W}{m \cdot K}\right] \qquad 8$$

which is a very good value for epoxy (Intel quote 0.58-0.67 for the materials they use, and Kyocera mention values of 0.6-0.9 in their sales literature). The accuracy of the value obtained above depends on the accuracy of the layer thickness only, and on the basis of the photographs of the chip cross sections kindly published by *Tomchr*, one can consider the value of 0.5 mm is a conservative estimate.

Having the respective thickness values of the epoxy layers in the various parts of the IC assembly makes it now possible to calculate the thermal resistance of the package clamped into the metal cooling block. Starting with the upper part of the tab, with the data:
$h_1 = 1.5\ [mm]$ – epoxy layer thickness at the upper side of the tab, and
$A_1 = 20 \cdot 8.6 - 0.5 \cdot 3.05^2 = 167\ [mm^2]$ – heat transfer area, we have

$$R_{th,1} = \frac{h_1}{k_e \cdot A_1} = 6.9\ \left[\frac{K}{W}\right] \qquad 9$$

This thermal resistance works in parallel to the existing one, and the resultant thermal resistance for the package with the upper part of the tab clamped onto the block is:

$$R_{th,0,1} = \frac{1}{\frac{1}{R_{th,0}} + \frac{1}{R_{th,1}}} = 1.55\ \left[\frac{K}{W}\right] \qquad 10$$

which is a reduction of 22.5% from the value quoted for cooling the back surface of the package only.

Adding now the heat transfer through the rest of the upper surface, with the data:
$h_2 = 2.5\ [mm]$ – epoxy layer thickness at the upper side of the package proper, and
$A_2 = 20 \cdot 10.7 = 214\ [mm^2]$ – heat transfer area, we obtain

$$R_{th,2} = \frac{h_2}{k_e \cdot A_2} = 9\ \left[\frac{K}{W}\right] \qquad 11$$

and

$$R_{th,0,1,2} = \frac{1}{\frac{1}{R_{th,0,1}} + \frac{1}{R_{th,2}}} = 1.32\ \left[\frac{K}{W}\right] \qquad 12$$

Since the two lateral surfaces also partake in the heat transfer process, they must be included in the energy balance. They are slanted in the Tomchr's cross sections, but not with the National's sample that I have; however, this is not of much consequence in this case because the fixture is filled with silicon paste anyway. I therefore estimated the following data:
$h_3 = 2.5\ [mm]$ – epoxy thickness at the lateral sides of the package, and
$A_3 = 2 \cdot (17 \cdot 3.3 + 10.7 \cdot 1.2) = 138\ [mm^2]$ – heat transfer area, and obtain

$$R_{th,3} = \frac{h_3}{k_e \cdot A_3} = 13.9\ \left[\frac{K}{W}\right] \qquad 13$$

and finally, for the entire package

$$R_{th,0,1,2,3} = \frac{1}{\frac{1}{R_{th,0,1,2}} + \frac{1}{R_{th,3}}} = 1.2\ \left[\frac{K}{W}\right] \qquad 14$$

3. Closing remarks regarding LM3886 cooling data

There are some points regarding the LM3886TF cooling data that merit further discussion, the first one being the value of the thermal resistance itself. As remarked previously, the figure of 2 K/W is quoted as an approximate value in the AN-1192 Application Report. However, in the original press release on the occasion of the launch of the plastic package in November 1995, its thermal resistance was quoted at 1.6 K/W, and claimed to be comparable to the one of the T package with a mica washer underneath (http://newscenter.ti.com/index.php?s=32851&item=125812). Would this value have been used in the calculations presented in Sec. 2 above, the resultant thermal resistance of the package in a cooling block would have come quite close to 1 K/W, and from the lower side at that (~0.9 K/W).

There is also an inconsistence in Table 2 of AN-1192 as regards the power dissipation values for the T and TF packages. Departing from the 40 W dissipation figure for the T version quoted in the Table (presumably with a washer of 0.2 K/W, so $R_{th} = 1.2\left[\frac{K}{W}\right]$), it takes a TF package with 1.6 K/W in order to dissipate the 30 W given in the Table; and the 2 K/W package quoted in the text would dissipate mere 24 W. Obviously, TI operate with two thermal resistance values for the plastic package in the same document.

Finally, there is a problem in AN-1192 with the definition of the conditions for achieving the 125 W dissipation figure for LM3886. As stated in the text:

"Its power dissipation specification is derived from the IC's junction-to-case thermal resistance, θ_{JC} = 1°C/W, the maximum junction temperature, T_J = 150°C, and the ambient air, T_A =25°C.",

the heat transfer is defined in terms of the air temperature, which is incorrect. For the dissipation value quoted to be achieved, one must have a temperature of 25ºC at the back of the package (needed because the thermal resistance figure is quoted as "*junction-to-case*"), which is impossible to achieve for the package alone in still air, and thus a heat sink is absolutely necessary. Strictly speaking, the sink would have to be infinite, for only in this manner the temperature at the back of the package would equal the one of the ambient air, producing thus the temperature difference of 125 K required for achieving the dissipation power of 125 W.

To their defence, one should acknowledge that TI do mention in AN-1192 that *"The data shown below should only be used as a guideline of possible IC power dissipation capability. Your electrical design parameters and thermal management may be different, changing the achievable results. As always, lab testing is recommended to verify any solution."*

And this is exactly what has been done in the case of the copper block cooling fixture that triggered the discussion in diyAudio.com.