Budapest University of Technology and Economics
Department of Electron Devices

BSc Course in Microelectronics

Laboratory Practice: Thermal Issues of Integrated Circuits

- Read through this summary carefully and answer the questions listed on the last page (similar questions are expected at the entry exam)
- Visit `edu.eet.bme.hu`, download and watch the video guide about how to use the THERMAN software.

Heat transfer methods

It is well known that heat transfer may be occurred by three different physical methods: *conduction*, *convection* and *radiation*. As a result of the heat transfer heat current is developed. Heat current density, denoted by **q** is the heat current flowing through the unit area during the unit time. It has a dimension of $[W/m^2]$.
The heat current density values of the different heat transfer mechanisms can be calculated as follows:

The conductive heat transfer

$$q = -\lambda \cdot gradT$$

where T is the temperature, λ $[W/m^2K]$ is the heat transfer coefficient. Note, that λ is a material property.

The convective heat transfer

$$q = h(T - T_\infty)$$

where T is the temperature of the surface which loses heat while T_∞ is the ambient temperature, which is treated to be constant, h is the convective heat transfer coefficient.
Convective heat transfer can be divided into two typical forms:

- *Natural convection* is a mechanism, or type of heat transport, in which the fluid motion is not generated by any external source (like a pump, fan etc.) but only by density differences in the fluid (liquid or gas) occurring due to temperature gradients. In natural convection, fluid surrounding a heat source receives heat, becomes less dense and rises. The surrounding, cooler fluid then moves to replace it. This cooler fluid is then heated and the process continues, forming a convection current; this process transfers heat energy from the bottom of the convection cell to top.
- *Forced convection* is a mechanism, or type of transport in which fluid motion is generated by an external source (like a pump, fan etc.). It should be considered as one of the main methods of useful heat transfer as significant amounts of heat energy can be transported very efficiently and this mechanism is found very commonly in everyday life, including central heating, air conditioning, steam turbines and in many other machines.

  Note: The current generated by forced convective heat transfer is caused by an external potential difference (e.g. pressure difference), just like the drift current in the semiconductors is generated by the potential of external voltage.

The Radiation

$$q = \varepsilon \sigma T^4$$

where $\sigma = 5.67 \cdot 10^{-8} W/m^2K^4$ the Stefan-Boltzmann constant, ε is the emissivity coefficient. If the surface is a perfect mirror ε equals to zero, while the perfect black body has an ε of 1.

In case of investigation the thermal transfer behavior of electronic devices, the following rule of thumbs may be applied:

- **Within the IC package (chip, chip assembly, bonding wires or bonding balls) only conductive heat transfer should be considered.**
  Heat generation within the chip depends on the function. Small signal analog circuits (e.g. operational amplifiers) typically generate heat below 500 mW. Simple digital circuits (TTL or CMOS logic gates) never exceed the 2 W dissipation. However analog switches may dissipate tens of Watts, as well as complex digital circuits, like a CPU.
- **Outside the package both conduction and convection are present. Heat transfer occurs through the package (natural convection) and through the device pins across the PCB (conduction).**
  High power devices (high current switching transistors, CPUs, GPUs) request cooling in order to keep the temperature of the device in the safe operation area. In case of non-military devices this temperature typically falls in the 0 to 70^oC range.
- Without a heatsink only $2-5W$ of power can be dissipated. With a heatsink the dissipable power may increased up to $10W$ (mainly natural convection).
- **Higher powers (up to $100W$) can only dissipated by using cooling fans. In this case the forced convection dominates over the heat transfer.**
- **Radiation should be take into consideration when heat transfer occurs through big surfaces** (e.g. LED lighting panels).

Boundary conditions

Heat transfer issues can be investigated by computer simulation methods. The problem should be isolated at first which consists the following restricions:

- It should be decided, what is the physical volume to be considered. With other words, where are the borders of the simulation domain (volume) where the effects of the outside world can be neglected therefore the domain is separated from the outside world.
- It should be decided, how the borders of the simulation domain connect to the outside world. These are called the boundary conditions. In case of thermal investigation these are typically Neumann, Dirichlet or Robin cases.
- Note, that in many cases despite the simulation gives some results the real world measurements may show quite different values. These errors are usually consequences of badly changed simulation domain or boundary conditions rather than the fault of the simulation software itself.

The boundary conditions can be divided into three groups

First order or Dirichlet boundary condition. The temperature function is prescribed at the boundary. If $T(x,t) = const$ the boundary condition is isometric.

$$T(x,t) = f(x,t) \tag{1}$$

Second order or Neumann boundary condition. The heat current density function is prescribed at the boundary. If $q(x,t) = 0$ the boundary condition is adiabatic (no heat loss from the system).

$$-\lambda \frac{\partial T}{\partial n} = q(x,t) \tag{2}$$

where n is the normal vector.

Third order or Robin boundary condition. The convection heat current density function is prescribed at the boundary.

$$-\lambda \frac{\partial T}{\partial n} = h(T(x,t) - T_\infty) \tag{3}$$

Compact models

There are some cases when simulations are not necessary to describe the thermal behavior of a system, obviously not in simple cases (e.g. a simple transistor in the circuit dissipates 5W, how big heatsink is requested?). Complex heat transfer methods may be simplified under given circumstances. If the path of the heat transfer may treated to be one dimensional, the conduction heat transfer can be described by thermal resistances. Consider a brick shaped heat conductor body with a temperature difference between its ends of $\Delta T = T_H - T_C$. Because of the temperature gradient heat current of P develops (remember, how the charge carrier concentration gradient causes electric current!).

$$R_{th} = \frac{\Delta T}{P} = \frac{L}{\lambda A}[K/W] \tag{4}$$

where $L[m]$ is the length and $A[m^2]$ is the cross-sectional surface of the brick.
Obviously the temperature of a body cannot change immediately, because the body itself should be filled of heat. The ability of a body to store heat is the heat capacitance. To rise up the temperature of the body by ΔT, a sum of W energy is requested:

$$C_{th} = \frac{W}{\Delta T} = c_v \cdot A \cdot L \tag{5}$$

where $c_v[W/(m^3 * T)]$ is the volumic heat capacity.
The thermal time constant is analogous the time constant of an R-C circuit as follows:

$$\tau_{th} = R_{th} C_{th} \tag{6}$$

The heat which is generated within the chip structure should be transferred to the ambient otherwise the temperature of the chip rises above the safe operation area. It depends on two factors:

- How the heat can be transferred from the chip (or more precisely, the place where the heat is generated: the p-n junction) to the chip package (or case): R_{thjc} (read: thermal resistance junction to case).
- How the heat can be transferred towards from the case to the ambient (it depends on the size of the heatsink, convective heat transfer etc..): R_{thca} (read: thermal resistance case to ambient)

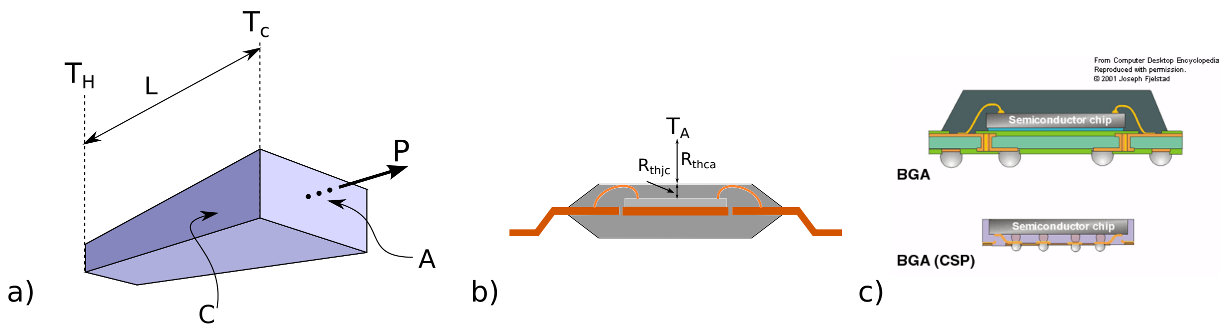

Figure 1: a) Understanding thermal resistance b) DIP package cross section and R_{thca}, R_{thjc} values c) modern BGA and BGA flip chip cross sections

R_{thjc} and R_{thca} are shown on the device's datasheets. Let's consider a device dissipating $100mW$ in DIP package, having $R_{thjc} = 37K/W$ and $R_{thca} = 70K/W$. What will be the junction temperature, if the ambient temperature is 25^oC?

$$T_j = T_{amb} + P(R_{thjc} + R_{thca}) = 25 + 10.7 = 35.7^oC \tag{7}$$

Temperature aware design of integrated circuits

It is a well known fact that the concentration of minority carriers have a strong temperature dependence through the temperature dependence of n_i^2 (where n_i is the intrincsic electron concentration).
Based on these effects the forward voltage characteristic of the p-n junctions (diodes, bipolar transistors) show

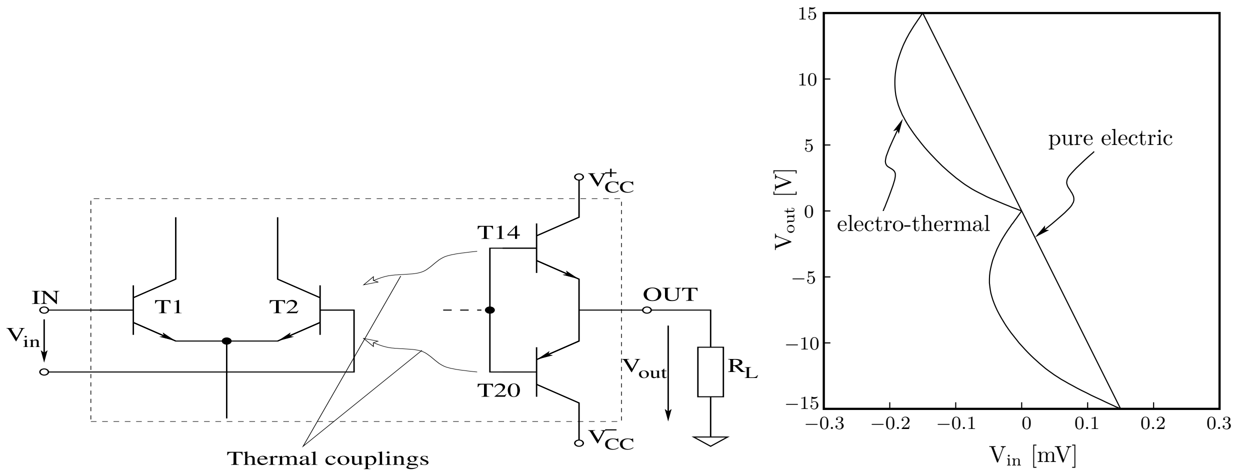

Figure 2: Thermal feedback in an op-amp – a typical situation, where there is a significant difference in the results between "electrical-only" and electro-thermal simulations

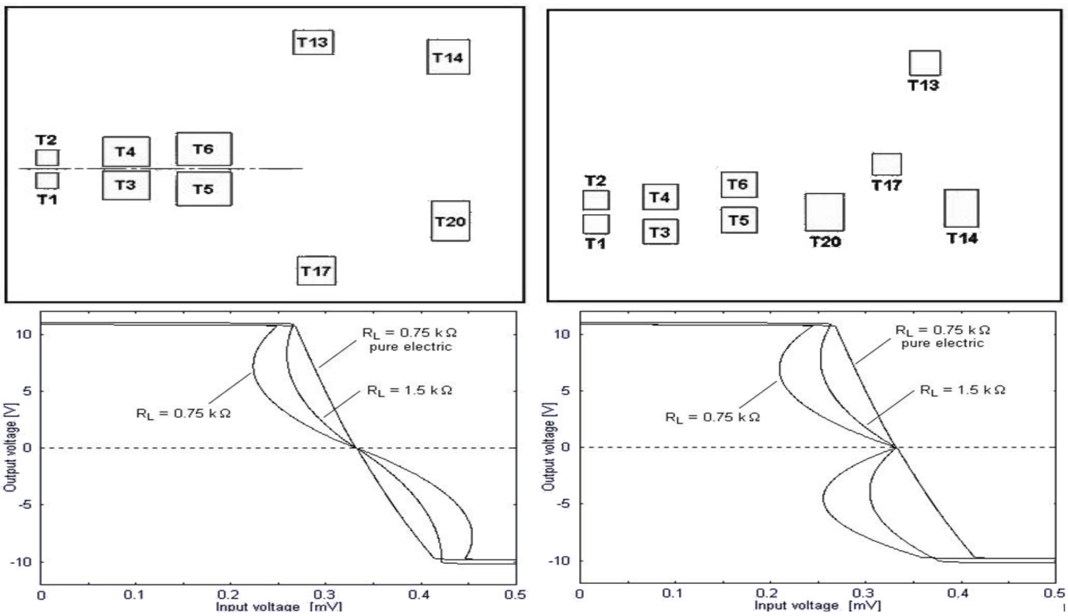

Figure 3: The two different layouts for the μA741 and transfer characteristics with different loads

also a non-neglible temperature dependence.
The forward voltage of the silicon diode shows about $-2mV/K$ temperature dependence.
Symmetric devices, like operational amplifiers request very good matching components in order to work correctly (imagine a badly balanced teeter: in order to work correctly, the two sides should be equal). As the characteristics of the components have temperature dependence, they should be at the same temperature otherwise they don't mach anymore.

The importance of thermal aware design at chip level can be easily demonstrated with the example of a simple op-amp (Fig. 2) – which is an ideal benchmark circuit for electro-thermal circuit simulators because it is highly sensitive to thermal offset. The relatively high dissipation of the output stage (T14, T20) warms up the input stage (T1, T2) which moves the operating points and thus changes the transfer characteristics. This effect strongly depends on the layout of the circuit.

The layout of the same circuitry is shown in two different version which gave us the ability to compare the results at different thermal scenarios. The simulated open-loop transfer characteristics can be seen with different loads. These results demonstrate that the structure of the physical layout has a major effect on the electrical behaviour through thermal coupling. Using the symmetric layout the output characteristics remains symmetric regardless the load applied while the asymmetric layout causes asymmetric output characteristics.

1 Questions

1. What are the main heat transfer methods? Describe the conductive (/convective/radiation) heat transfer and relevant equations.
2. What are the main types of convective heat transfer? What is the main difference between them?
3. What types of heat transfer should be considered at different stages of an electronic system?
4. What are boundary conditions? Why they should be used?
5. Describe the first (/second /third) order boundary condition and relevant equations.
6. What are compact models? Under what circumstances should they be used?
7. Describe the compact model approach of thermal resistance (/thermal capacitance) and relevant equations.
8. What is the thermal time constant and how to calculate it?
9. What are main factors which describe the heat transfer ability of a package?
10. A transistor dissipates 1 W, the ambient temperature is 25^oC, $R_{thjc} = 40K/W$. What is the requested value of R_{thca} if the junction temperature should not exceed 60^oC?
11. Why the temperature aware design of analog circuits is important?

References

[1] A. Szalai, Z. Czirkos, V. Szekely: A quasi-SPICE electro-thermal simulator, 18th International Workshop on Thermal investigations of ICs and Systems, 2012, Budapest, Hungary