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Dynamical cooling of semiconductor by contact layer

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Abstract

The subject of this paper is the presentation of a simple theoretical model of cooling of a semiconductor. The problem of the unsteady behaviour both of the semiconductor and of the cold plate that are in touch by the contact layer was studied analytically. The influence of the parameters of the materials and the cooling conditions was investigated. The results in the form of an analytical formula and graphs are presented and the heat stream is compared with the experimental results.

1. Introduction

One of the most important problems in computers is the cooling of electronic devices and the limitations on maximum temperature. Semiconductor elements, which are self-heated when the computer is working, belong to these devices. Their temperature cannot exceed the acceptable value to secure correct work of a computer. The solution to the cooling problem is very important for the proper work of computer elements, which get heated in time with a variable intensity. The intensity of heating of semiconductor elements (chips) depends on their usage. The dynamical cooling of the semiconductor in a computer is very much required.

A commonly used innovative cooling technique by using the forced air-cooling technology was developed in [1]. Recently, an investigation was carried out to develop an MEMS (Micro-Electro-Mechanical Systems) based micro cooling device [2]. This new method is a very efficient technique to remove heat from chips by surface evaporation of the chilling liquid. Amount heat, which flows away from the elements, depends still on the contact layer between the chip and the cooling substance. On the boundary of two bodies, a contact layer is always present.

Another way of cooling the chip is use the cold copper plate, which is in contact with the semiconductor. The cooling water flows in the channel inside the plate. Contact resistance is observed between the chip (semiconductor) and the copper plate. The problem of contact resistance is also present in manufacturing technology of circuit element electronics and during the first stages of metal solidification process. This issue was studied in [3–7]. The role of the contact layer between the cooper plate and the semiconductor is very important in the process of heat transfer. The present study focuses on the prediction of temperatures of both the copper plate and the semiconductor depending on time. The heat storage of the plate, which accumulates a great part of the heat, is of great importance.

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Nomenclature

$\dot{Q}$	heat stream (W)	λ	heat conduction coefficient (W/(m °C))
F	surface (m^2)	c	specific heat (J/(kg °C))
T	temperature (°C)		
m	mass (kg)	*Subscripts*	
t	time (s)	W	water
H	thickness of plate (m)	C	chip
δ	thickness of contact layer (m)	p	paste
α	coefficient of heat transfer (W/(m^2 °C))	ch	channel

2. Presentation of the problem

The copper plate has the mass m, which is much larger than the mass of the chip. The chip is in very good heat contact with the plate thanks to the contact paste, which is between these elements. The semiconductor during its work generates heat. The cooling water flows inside the copper plate (Fig. 1).

The instantaneous heat $\dot{Q}$ from the semiconductor chip is transferred to both the copper plate and the cooling water. The energy balance may be described by two equations:

$$\dot{Q} = \alpha_p \cdot (T_C - T) \cdot F_C(\alpha_p = \alpha_{p0} + k \cdot (T + T_C)/2),$$
$$\dot{Q} = c \cdot m \cdot \frac{dT}{dt} + \alpha \cdot F_{ch} \cdot (T - T_W), \tag{1}$$

where α, α_p are the coefficients of heat transfer for both the water in the channel and the paste, T, T_C, T_W are the temperatures of the copper plate, the chip and water, F_{ch}, F_C, F are the surfaces of the side channel, the contact surface and the cooper plate, c is the specific heat of the copper, m is the mass of the copper plate, t is the time. The contact layer from the point of view of heat transfer is describes by the value $\alpha_p = \alpha_{p0} + k \cdot (T + T_C)/2$, where the parameter $\alpha_{p0} = 1/(R_g + \delta_p/\lambda_p)$, λ_p is the heat conduction coefficient and δ_p is the thickness of the contact layer, R_g is the additional resistance of the gap of air.

The following sets of dimensionless parameters were introduced: the copper temperature, semiconductor temperature, water temperature, time that is equal the Fourier number

$$\theta = \frac{T - T_W}{T_{in} - T_W}, \quad \theta_C = \frac{T_C - T_W}{T_{in} - T_W},$$
$$\theta_W = \frac{T_W - T_W}{T_{in} - T_W} = 0, \quad \tau = Fo = \frac{a \cdot t}{H^2},$$

where H is the cold plate thickness, a is the thermal diffusivity of the cold plate, T_{in} is the initial temperature.

Finally, we receive in a dimensionless form the set of two equations, which describe the distribution of temperatures

$$\theta_C^2 + \frac{\tilde{\alpha}_0}{\tilde{\alpha}_1}\theta_C - \theta^2 - \frac{\tilde{\alpha}_0}{\tilde{\alpha}_1}\theta - \frac{1}{\tilde{\alpha}_1 \cdot \tilde{f}_C}\dot{q}(\tau) = 0,$$
$$A \cdot \frac{d\theta}{d\tau} + \theta - \dot{q}(\tau) = 0 \tag{2}$$

where

$$\dot{q}(\tau) = \frac{\dot{Q}(t)}{\alpha \cdot F_{ch} \cdot (T_{in} - T_W)}$$

is the dimensionless heat stream, the remaining parameters of Eq. (2) are equal to, respectively:

$$A = \frac{c \cdot m \cdot a}{\alpha \cdot F_{ch} \cdot H^2}, \quad \tilde{f}_C = \frac{F_C}{F_{ch}},$$
$$\tilde{\alpha}_1 = \frac{k}{2\alpha}(T_{in} - T_W); \quad \tilde{\alpha}_0 = \frac{\alpha_{p0}}{\alpha}.$$

The parameter A depends on both the properties of the copper plate and the phenomenon of cooling; $\tilde{f}_C$ is the ratio the contact surface F_C between the chip and the copper plate and the lateral surface F_{ch} of the channel placed inside the copper plate, $\tilde{\alpha}$ is the ratio of the heat transfer parameters of the contact layer α_{p0} and $\alpha_{p1}/2 \cdot (T_{in} - T_W)$ to the heat transfer α in the water channel.

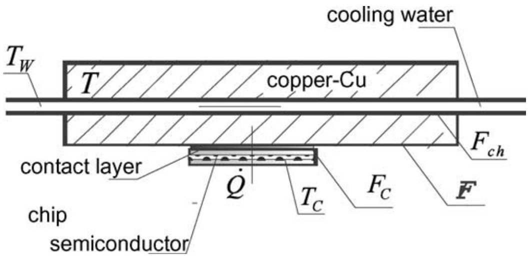

Fig. 1. Cooling of a semiconductor.

3. Solution of the problem

By solving the second equation from Eq. (2) and fulfillment the initial condition

$$\tau = 0 \Rightarrow \theta = 1 \tag{3}$$

we receive the analytical solution in the form

$$\theta = \exp\left(-\frac{\tau}{A}\right) \cdot \left[\frac{1}{A}\int_0^\tau \dot{q}(\tau)\cdot \exp\left(\frac{\tau}{A}\right)\cdot \mathrm{d}\tau + 1\right]. \quad (4)$$

For the constant heat stream, $\dot{q}(\tau) = \dot{q}_0 = \text{const}$ the distribution of the temperature has the simple expression

$$\theta = \dot{q}_0 - \dot{q}_0 \cdot \exp\left(-\frac{\tau}{A}\right) + \exp\left(-\frac{\tau}{A}\right). \quad (5)$$

Fig. 2 shows dependence of temperature on time in the graphical form. When the heat stream is equal to 1 the temperature does not depend on time. For heat streams larger than 1, the temperature rises exponentially with time and for large times, the temperature achieves a constant value. For heat stream less than 1, the temperature decreases exponentially also with time to the constant value.

The temperature in the semiconductor element θ_C is suitably larger than the temperature of the cooper plate θ, which by assumption is the same in the whole chip. The value of the temperature depends on the resistance of the contact layer paste between the plate and semiconductor element.

The non-dimensional heat stream $\dot{q}(\tau)$ is a very interesting quantity, especially its dependence on time. In practice, in a computer the system semiconductors work continuously. In the event of a heavy work burden for the computer, the quantity of generated heat increases. For example, the use of the processor in time is shown in Fig. 3. The stream of heat is proportional to the extend the computer is used. We can assume that the function for the heat is:

$$\dot{q}(\tau) = \dot{q}_0 + \dot{q}_a \cdot \sin(\omega\tau) \quad (6)$$

where $\dot{q}_o$ is the static heat stream, $\dot{q}_a$ is the amplitude of the changeable stream heat and ω is its frequency. Substituting this value into Eq. (4) we get

$$\theta = \exp\left(-\frac{\tau}{A}\right)\cdot\left[\frac{1}{A}\int_0^\tau (\dot{q}_0 + \dot{q}_a \sin(\omega\tau))\cdot\exp\left(\frac{\tau}{A}\right)\cdot \mathrm{d}\tau + 1\right]. \quad (7)$$

Eq. (7) after integration from 0 to τ gives

$$\theta = \dot{q}_0 - (\dot{q}_0 - 1)\exp\left(-\frac{\tau}{A}\right) + \frac{\dot{q}_a \cdot A}{1 + (A\omega)^2}\left[\frac{1}{A}\sin(\omega\tau) - \omega\cos(\omega\tau) + \omega\exp\left(-\frac{\tau}{A}\right)\right] \quad (8)$$

The solution of the first equation with Eq. (2) we have the temperature in the semiconductor

$$\theta_C = \frac{1}{2}\left[-\frac{\tilde{\alpha}_0}{\tilde{\alpha}_1} + \sqrt{\left(\frac{\tilde{\alpha}_0}{\tilde{\alpha}_1}\right)^2 + 4\cdot\left(\theta^2 + \frac{\tilde{\alpha}_0}{\tilde{\alpha}_1}\cdot\theta + \frac{\tilde{\alpha}_0}{\tilde{\alpha}_1}\cdot\frac{\dot{q}(\tau)}{\tilde{\alpha}_0\cdot\tilde{f}_C}\right)}\right] \quad \text{for } \tilde{\alpha}_1 \neq 0, \quad (9)$$

$$\theta_C = \theta + \frac{1}{\tilde{f}_C\cdot\tilde{\alpha}_0}\dot{q}(\tau) \quad \text{for } \tilde{\alpha}_1 = 0. \quad (10)$$

Figs. 4 and 5 present in a graphical form the solutions ((8) and (10)) for the different conditions of cooling. The temperature and its amplitude for the semiconductor is larger than the temperature and the amplitude for the cooper plate.

The frequency of the temperatures in the chip is larger than in the copper plate. The phase shift between the temperatures in the semiconductor and the cooper plate is present. The value of the temperature inside the semiconductor changes a great deal because of small inertia of this element as compared to the copper plate. The

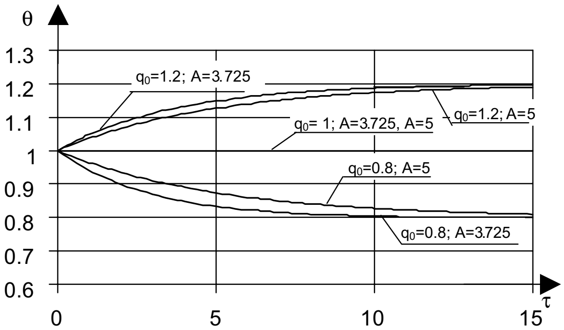

Fig. 2. Distribution of temperature in copper plate for constant streams.

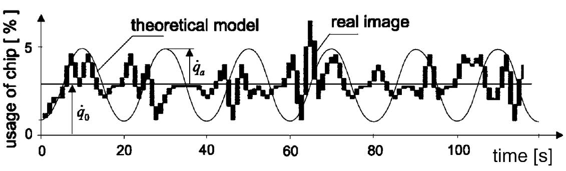

Fig. 3. Usage of the chip athlon XP 2400+.

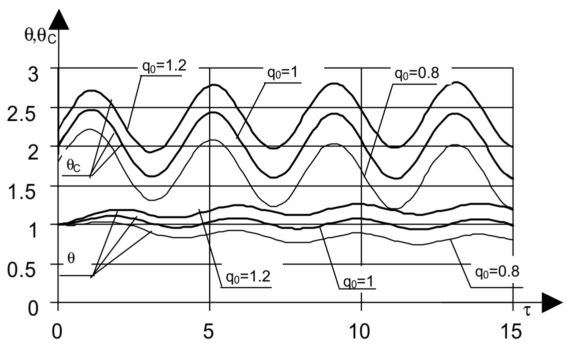

Fig. 4. Dependence of temperature on time with changeable of stream heat for $A = 3.725$, $\omega = 1.57$, $\tilde{f}_C\cdot\tilde{\alpha} = 1$, $\dot{q}_a = 0.4$.

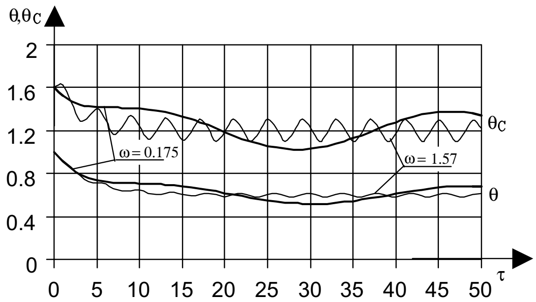

Fig. 5. Dependence of temperature on time with frequency for $A = 3.725$, $\tilde{f}_C \cdot \tilde{\alpha} = 1$, $\dot{q}_0 = 0.6$, $\dot{q}_a = 0.1$.

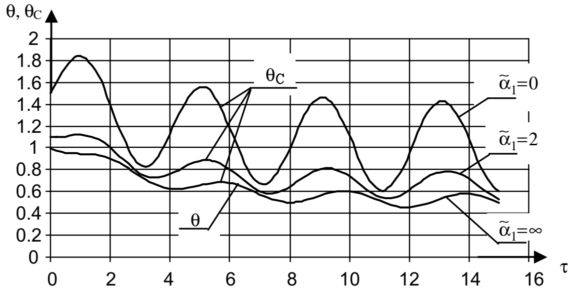

Fig. 6. Dependence of temperature on time for different of coefficients $\tilde{\alpha}_1$ for $A = 3.725$, $\omega = 1.57$, $\tilde{f}_C = 1$, $\tilde{\alpha}_0 = 1$, $\dot{q}_0 = 0.5$, $\dot{q}_a = 0.4$.

resistance of the paste in the contact layer between the plate and the chip decreases the heat flow. In that case, the temperature difference between the semiconductor and the copper plate $\theta_C - \theta$ increases.

Fig. 6 presents in a graphical form the solutions (8)–(10) for the different conditions of cooling. If there is used the theoretical model with the constant resistance of the heat ($\tilde{\alpha}_1 = 0$) the difference $\theta_C - \theta$ is bigger than for the resistance of the heat which depends on the temperature (for example $\tilde{\alpha}_1 = 2$). If the coefficient has the value, $\tilde{\alpha}_1 = \infty$ the curves of temperature are the same.

4. Results and conclusion

From above the theoretical analysis it follows that the distribution temperature in the processor depends on the cooling condition $\dot{q}(\tau)$, the parameter of the copper plate A, the ratio of the surfaces $\tilde{f}_C$ and the ratio the coefficients heat transfers $\tilde{\alpha}$. These parameters play an important role in the cooling of the semiconductor. A great deal of the heat capacity of the copper plate and its large inertia contribute to a decrease in the variations of temperature in the plate. A small inertia of the semiconductor results in its greater sensitivity to the work conditions of the computer. The temperature amplitude of the processor is relatively quite large in comparison with the plate. The solution of this problem is reduced mainly to determination of the contact resistance between the chip and the plate, which depends on both the kind of the past and the contact surface.

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