D. V. Fedasiuk, Dc. Sc. (Eng.), Prof.; T. O. Mukha

COOLING MODELING, USING LIQUID BOILING FOR HEAT TRANSFER INTENSIFICATION AT CRITICAL CONDITIONS IN MICROELECTRIC DEVICES

The paper considers non-stationary, non-linear model of heat exchange process in microelectronic devices, using liquid boiling for heat transfer intensification in critical conditions. For the analysis of the model the set of numerical methods has been used that enabled to obtain solution in numerical form. On the basis of constructed model temperature change and variation of heat fluxes, removed form the surface of the device in time and impact of boiling process on heat transfer is investigated.

Key words: *heat transfer, boiling, non-linear model, numerical methods, modeling.*

Problem set-up

Growth of heat release, observed in recent decade as a result of microminiaturization of electronic components, imposes constrains on power and speed of electronic devices, that is why, important problem is heat removal to provide corresponding temperature mode. If heat removal is not sufficient to provide corresponding temperature mode, then the temperature of the device growth, that can cause a failure. In such critical conditions there appears the necessity in additional heat removal, that would allow to decrease the temperature of cooled element.

Rapid cooling provides one of modern approaches to the problem of heat removal, when change of substance from liquid into gaseous is used. While changing of substance state, the removal of heat in the form of hidden energy of liquid evaporation occurs. Such heat removal is characterized by high coefficients of convective heat transfer. It includes evaporation of the liquid in hot region and condensation of vapour in cold region and provides removal of far more larger heat fluxes, than those removed as a result of forced convection of air or liquid.

Analysis of the research and publications

Already known research of heat removal process using evaporation are characterized by a variety of approaches. However, one part of research concentrate their attention on the process of evaporation [1 – 5], and heat transfer remains out of their attention. Another group of researches investigated only the process of stationary heat transfer [6 - 8], that limits the

Certain scientists, while constructing mathematical models make assumptions, that considerable simplifies the model [9, 10] but such simplification influences the adequacy of the results.

In [11] the model of heat transfer, taking into account the influence of liquid evaporation on the process of heat removal, has been constructed. But while model construction, the assumption was made regarding the absence of liquid boiling and the assumption that evaporator takes place at the expense of diffusion.

Due to the above-mentioned peculiarities there appears the necessity to construct mathematical model of heat transfer process, using liquid boiling for additional heat removal at critical conditions in microelectronic devices (MED).

Aim of research

The aim of research is elaboration of mathematical model of heat transfer in microelectronic devices using liquid boiling for intensification of heat removal in critical conditions.

Problem description

Microelectronic device (MED) is considered, its construction is shown in Fig. 1 [12]. Crystal, protected by the housing is mounted on the substrate. Heat removal from MED in the environment is provided by heat removing plate, connected to the housing of the crystal. To improve thermal contract and thermal conducting paste is between the plate and housing. When the temperature of the housing exceeds critical temperature, liquid is supplied on the surface of heat removing plate, providing as a result of boiling, additional heat removal.

For MED, the manufacturers specify either heat release power to be removed [13, 14] or heat flux, released by MED. The temperature of MED housing must not exceed the preset temperature level [15]. Temperature of MED housing exceeds critical in case, when heat removal is not sufficient to dissipate heat, released by MED. To remove heat, released by MED at critical conditions indirect liquid cooling, using liquid boiling is used, since such approach allows to avoid the contact of boiling liquid with MED. In [16] it is shown, that the usage for each heat releasing element of separate heat removing plate is the most efficient from the point of view of heat removing.

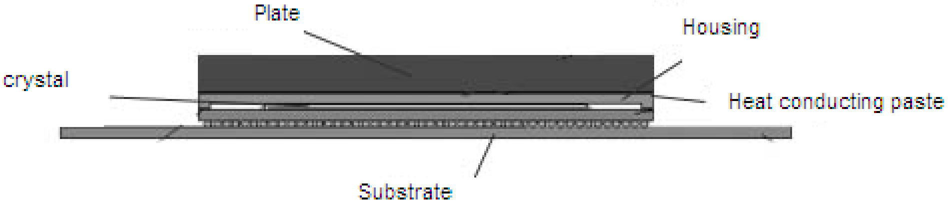

Fig. 1. Construction of MED

While modeling two models of heat transfer are taken into account: 1) in normal conditions when heat removal occurs due to convection; 2) while boiling of the liquid, that is supplied on the surface, on condition of exceeding the critical temperature. Boiling of liquid provides additional heat removal at critical conditions in MED. Thermal model of MED is presented in the from of infinite plate (Fig. 2), thickness of the plate being D. The plate is heated from below by heat flux of q_0 value. Till the temperature is less than critical, heat is removed from the surface of the plate due to convection. At the initial moment of time, the plate has uniform temperature T_b. When the temperature of lower surface of the plate becomes higher than T_{cr}, on the upper surface the liquid, is poured, as a result of its boiling heat is removed. The created layer of liquid has far less thickness, than the thickness of the plate. Ambient temperature – T_∞, atmospheric pressure – P_{atm}. Thermal conductivity of the plate, density and specific heat depend on the temperature. While construction of the model the assumption is made [17, 18] that heat transfer occurs only along axis x, as a rule, the thicknes of the plate is far more less than the width and length.

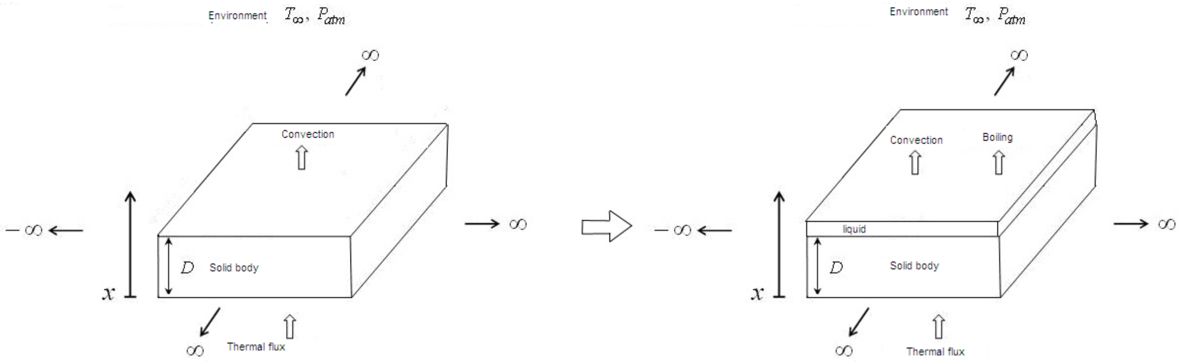

Fig. 2. Thermal model of MED

Heat conduction in conventional mode is describe by the following non-linear differential equation in partial derivatives, initial and boundary conditions:

$$c_s(T_1)\rho_s(T_1)\frac{\partial T_1}{\partial t} = \frac{\partial}{\partial x}\left(k(T_1)\frac{\partial T_1}{\partial x}\right), \qquad (1)$$

$$k(T_1)\frac{\partial T_1}{\partial x}\bigg|_{x=0} = -q_0'', \tag{2}$$

$$-k(T_1)\frac{\partial T_1}{\partial x}\bigg|_{x=D} = q_{conv}'', \tag{3}$$

$$T_1(x, t=0) = T_b, \tag{4}$$

where $T_1 = T_1(x,t)$ – is the temperature of the plate at the point with coordinate x, at the moment of time t in conventional mode; $k(T_1), c_s(T_1), \rho_s(T_1)$ – thermal conductivity $[W/m \cdot K]$, specific heat$[J/kg \cdot K]$ and density $[kg/m^3]$ correspondingly, q_0'' – is the value of heat flux transferred from MED to heat removal plate $[W/m^2]$, q_{conv}'' – is heat flux, removed from the surface due to convection$[W/m^2]$, T_b – is initial temperature of the plate $[K]$.

Using liquid boiling for heat removal intensification, the process oh heat conduction in critical mode is described by such equations:

$$c_s(T_2)\rho_s(T_2)\frac{\partial T_2}{\partial t} = \frac{\partial}{\partial x}\left(k(T_2)\frac{\partial T_2}{\partial x}\right), \tag{5}$$

$$k(T_2)\frac{\partial T_2}{\partial x}\bigg|_{x=0} = -q_0'', \tag{6}$$

$$-k(T_2)\frac{\partial T_2}{\partial x}\bigg|_{x=D} = q_{conv}'' + q_{boil}'', \tag{7}$$

$$T_1(x, t=t_{cr}) = T_2(x, t=t_{cr}), \tag{8}$$

where $T_2 = T_2(x,t)$ – is the temperature of the plate at the point with the coordinate x at the moment of time t at critical mode, q_{boil}'' – is heat flux, removed from the surface due to boiling $[W/m^2]$.

Heat flux, removed as a result of convection, according to Newton's law, is founf from the equation:

$$q_{conv}'' = h(T_i(D,t) - T_\infty),\ i = 1,2, \tag{9}$$

where h – is coefficient of convective heat transfer with the environment $[W/m^2 \cdot K]$, T_∞ – is the temperature of the environment, $i = 1$ for conventional mode and $i = 2$ for critical mode.

Heat flux, removed as a result of liquid boiling is found [17]

$$q_{boil}'' = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_\upsilon)}{\sigma}\right]^{\frac{1}{2}}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f} h_{fg} \Pr_l^n}\right)^3, \quad T_2 \geq T_{boil} + 5, \tag{10}$$

where h_{fg} – is specific heat of liquid evaporation $[J/kg]$, μ_l – is liquid viscosity $[kg/c \cdot m]$, g – is free fall acceleration $[m/c^2]$, ρ_l, ρ_υ – is density of boiling substance in liquid and gaseous states $[kg/m^3]$ correspondingly, σ – is surface tension of the liquid $[H/m]$, $c_{p,l}$ –is specific heat of the liquid at constant pressure, ΔT_e – is the difference between the temperature of upper surface of the plate and the temperature of liquid boiling, $C_{s,f}$, n – are constants, found exoeruimentally for each pair surface-liquid, $\Pr_l$ – Prandtl number for liquids.

For analysis of non—linear non-stationary model of heat transfer process in MED using boiling the totality of numerical methods is applied: for time sampling – Rote method, for spatial digitization – net point method. The specific feature of net-point method application to non-linear mathematical model of heat transfer in MED using boiling for intensification of heat removal is the necessity to apply iteration methods for solution of the system of non-linear differential equations.

Results of modeling

While modeling the following values of input parameters of model experiment and parameters of model experiment and values of thermal physical properties of materials are used:

$T_b = 293\ {}^0K$, $T_\infty = 293\ {}^0K$, $D = 0{,}01\,м$, $q_0'' = 100000\ \left[Вт/м^2\right]$.

Material of heat removal plate – copper:

$k_s = 401\ \left[W/m\cdot K\right]$, $c_s = 8933\ \left[J/kg\cdot K\right]$, $\rho_s = 385\ \left[kg/m^3\right]$.

Ethanol [19]:

$h_{fg} = 846000\ \left[J/kg\right]$, $\mu_l = 0{,}000592\ \left[kg/c\cdot m\right]$ [20], $\rho_l = 757$, $\rho_\upsilon = 1{,}44\ \left[kg/m^3\right]$, $\sigma = 0{,}0177$ $\left[H/m\right]$ [17], $c_{p,l} = 2470\ \left[J/kg\cdot K\right]$, $C_{s,f} = 0{,}0027$, $n = 1{,}7$, $\Pr_l = 8{,}12$ [21], $T_{boil} = 351\ {}^0K$.

Acetone [22]:

$h_{fg} = 501000\ \left[J/kg\right]$, $\mu_l = 0{,}000316\ \left[kg/c\cdot m\right]$ [23], $\rho_l = 790$, $\rho_\upsilon = 2{,}33\ \left[kg/m^3\right]$, $\sigma = 0{,}02346\ \left[H/m\right]$, $c_{p,l} = 2150\ \left[J/kg\cdot K\right]$, $C_{s,f} = 0{,}013$ [24], $n = 1{,}7$, $\Pr_l = 4{,}22$, $T_{boil} = 330\ {}^0K$.

FC-72 [25]:

$h_{fg} = 88000\ \left[J/kg\right]$, $\mu_l = 0{,}00064\ \left[kg/c\cdot m\right]$, $\rho_l = 1680$, $\rho_\upsilon = 13{,}55\ \left[kg/m^3\right]$, $\sigma = 0{,}01\ \left[H/m\right]$, $c_{p,l} = 1100\ \left[J/кg\cdot K\right]$, $C_{s,f} = 0{,}0055$ [26], $n = 1{,}7$, $\Pr_l = 12{,}35$, $T_{boil} = 329\ {}^0K$.

FC-87 [27]:

$h_{fg} = 103000\ \left[J/кg\right]$, $\mu_l = 0{,}00045\ \left[kg/c\cdot m\right]$, $\rho_l = 1650$, $\rho_\upsilon = 11{,}55\ \left[kg/m^3\right]$, $\sigma = 0{,}009$ $\left[H/m\right]$, $c_{p,l} = 1100\ \left[J/kg\cdot K\right]$, $C_{s,f} = 0{,}0055$ [26], $n = 1{,}7$, $\Pr_l = 8{,}84$, $T_{boil} = 303\ {}^0K$.

Water [17]:

$h_{fg} = 2257000\ \left[J/kg\right]$, $\mu_l = 0{,}000279\ \left[kg/c\cdot m\right]$, $\rho_l = 1044$, $\rho_\upsilon = 1{,}679\ \left[kg/m^3\right]$, $\sigma = 0{,}0589$ $\left[H/m\right]$, $c_{p,l} = 4217\ \left[J/kg\cdot K\right]$, $C_{s,f} = 0{,}0128$, $n = 1{,}0$, $\Pr_l = 1{,}76$, $T_{boil} = 373\ {}^0K$.

Fig. 3 shows temperature variation of heat removal on lower surface with time, since on lower surface of the plate the temperature is the highest. Unlike evaporation, that occurs at any temperature, boiling of the liquid is possible only when the temperature of heat removal plate becomes higher than boiling temperature. That is why, liquid is supplied at the moment, when the temperature of the plate exceeds boiling temperature. After that, the temperature of the plate grows slower, as heat is additionally removed due to liquid boiling. Temperature growth is stopped, when the difference between the temperature on upper surface of the plate and the temperature of liquid boiling reaches the value, that provides the removal of necessary heat flux. The lower the temperature of liquid boiling, the less temperature is established while using boiling for heat removal intensification.

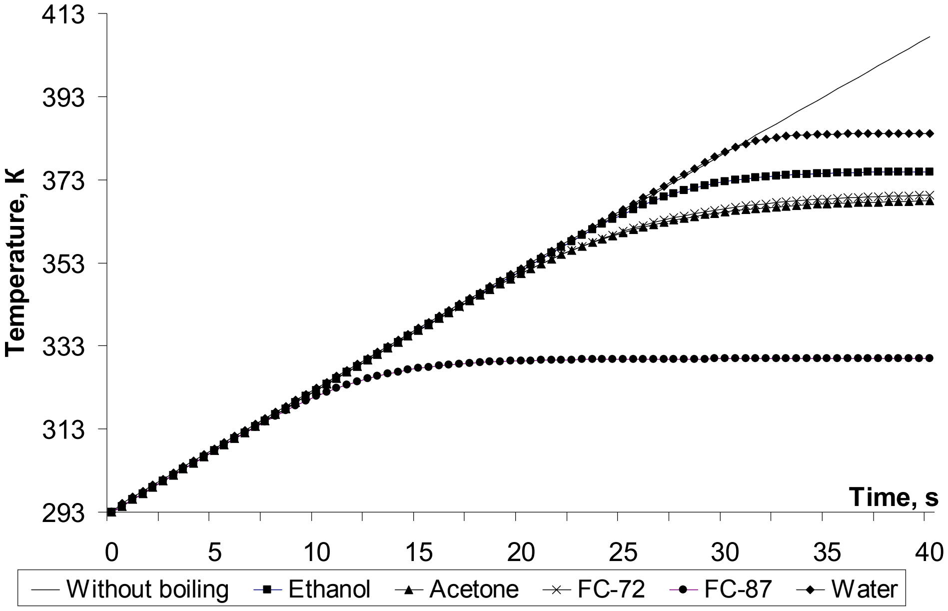

Fig. 3. Temperature variations while boiling usage

Fig. 4 shows variation of heat fluxes values, removed by heat removal plate in the environment, with time, while usage of different liquids boiling for heat removal intensification. Prior to boiling of the liquids, heat is removed due to convective heat transfer between the surface of heat removal and ambient air. Heat flues, being removed are small, as compared with heat fluxes, removed while liquid boiling. After supply of the liquid on the surface of the plate heat removal drastically increases, until it reaches the value, that equals the value of heat flux, released by heat releasing elements.

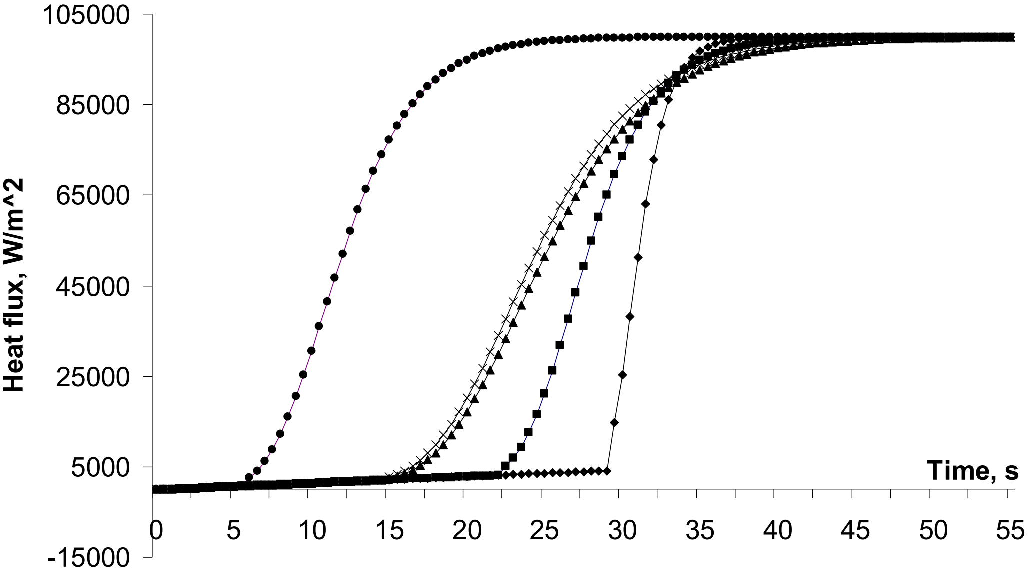

Fig. 4. Fluxes, removed while liquid boiling for additional heat release

Since liquid FC-87 provides the least temperature among liquids, used in the process of research, then the analysis of the influence of flux value on q''_0 temperature change with time, was carried out using this liquid.

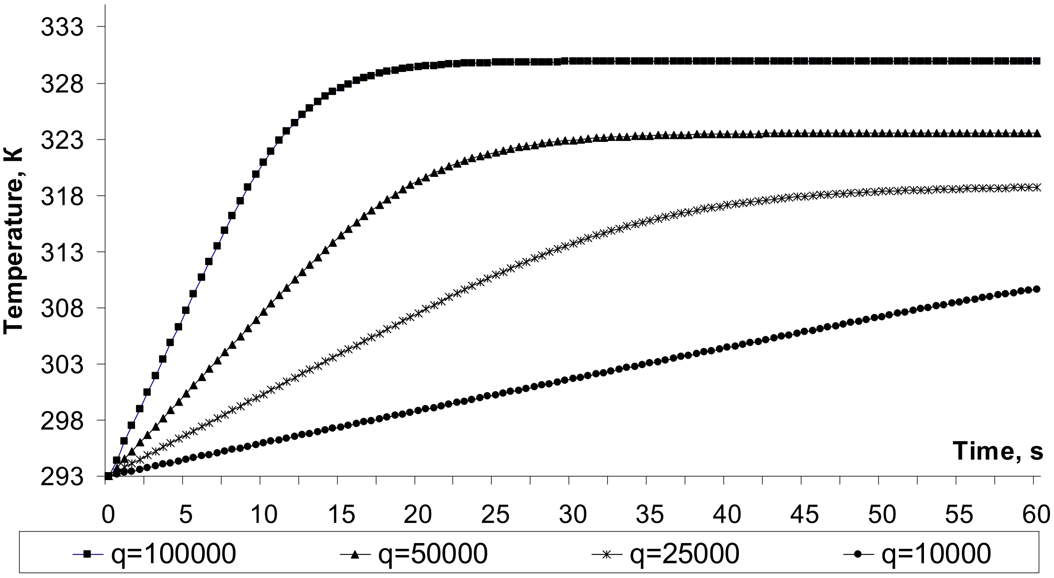

Fig. 5. Influence of the flux on temperature change for FC-87

The larger heat flux, heating the plate, more rapidly the temperature of the plate becomes equal boiling temperature. After using boiling for intensification of heat removal, the temperature of the plate reaches the value, at which flux, removed from the surface of the plate as a result of boiling and convection, becomes equal heat flux, released by heat releasing element. That is why, the greater heat flux heats the plate, the greater temperature difference is required while boiling to remove it. The smaller is flux q_0'' value, the less plate temperature is while balancing fluxes as less temperature difference is required for this.

Conclusions

Non-linear, non-stationary model of heat transfer process using liquid boiling for intensification of heat removal in MED at critical conditions is constructed. The model takes into account the influence of liquid evaporation while boiling on heat removal process at critical conditions, dependence of thermal physical parameters and the value of heat flux, removed as a result of boiling, on the temperature. The constructed model enables to study temperature changes in MED and variations of heat fluxes, removed the surface of MED, with time, and to study the influence of boiling process on heat process. The efficiency of liquid boiling usage for intensification of heat removal at critical conditions it is shown.

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Fedasiuk Dmytro – Dc. Sc. (Eng.), Professor, Head of Software Department, e-mail: fedasyuk@lp.edu.ua, тел. (032) 258-24-12.

Mukha Taras – Assistant, Software Department, e-mail: muha_taras@rambler.ru, тел. (032) 285-25-78.
National University ”Lvivska Politechnika”