CHARACTERISATION OF THERMAL EQUIVALENT CIRCUIT FOR SPICE-LIKE ELECTRO-THERMAL MODEL OF POWER MOSFET

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1. Introduction

Today's circuit simulators are standard tools in the development and optimization of electronic systems. However, the simulation has been limited until now to electronic functions because, in the simulation models available today, temperature dependence can be taken into account at best by changing the static global temperature. In power-electronic systems in particular, the temperature is one of the critical parameters due to the fact that many properties of power semiconductors are very strongly temperature-dependent [1].

In this paper we described new SPICE-like simulation models which contain a dynamic link between electrical and thermal component descriptions. Two thermal equivalent circuit diagrams were designed for a power MOSFET. The possibilities and limitations of the new models are analyzed and presented.

2. Electrical equivalent of a thermal system

A thermal system can be usually modeled with a discrete element electrical circuit, composed by resistances and capacitances, in which the temperatures and the thermal powers are retained as voltages and currents, respectively (Fig. 1). The electrical current generator source *I(t)* corresponds to the thermal power in the heat source *P(t)*. The resistances R_i and capacitances C_i represent the thermal resistances R_{thi} and thermal capacitances C_{thi} of the structure. Due to a close relationship with physical reality of the one-dimensional heat flow, the parameters for the RC equivalent circuit diagram can be derived directly from the Eq.(1) and Eq.(2), where A is the surface, d_i is the thickness, κ and c are the thermal conductivity and heat capacity of the elements. The voltage in the V_j node represents the temperature T_j in the heating spot. Then we can define:

$$R_i \approx R_{th\,i} = \frac{d_i}{\kappa \cdot A}\,;\; C_i \approx C_{th\,i} = c \cdot d_i \cdot A \tag{1}$$

$$I(t) \approx P(t)\,;\; V(0,t) \approx T(0,t)\,;\; V_j \approx T_j \tag{2}$$

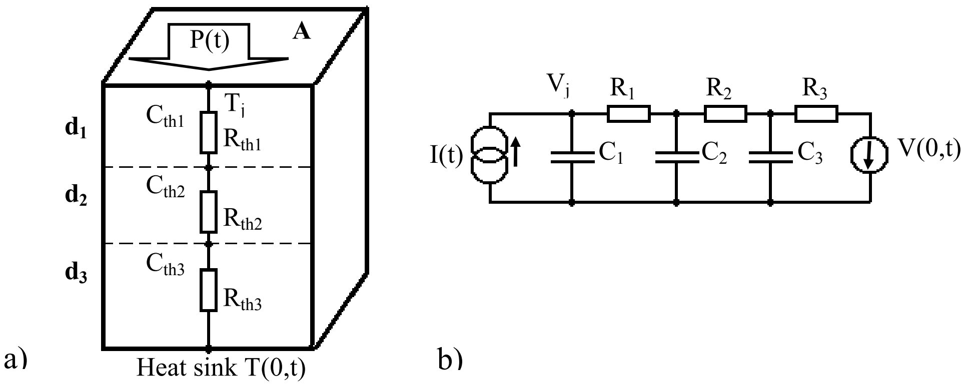


Fig.1: *a) Thermal structure, b) electrical equivalent of the thermal system.*

3. Experiment

The structure under investigation is the trench MOSFET power transistor in the DPAK2 package. The standard equivalent circuit diagram of the vertical structure for SPICE-like circuit simulation is shown in the Fig. 2a. In order to be able to simulate the inherent heating dynamically, an interactive coupling of the thermal description with the MOSFET model is necessary as shown schematically in Fig. 2b. The power dissipation in the transistor is determined at all times and a current proportional to the dissipated power is fed into the thermal equivalent network. The V_j node voltage represents the junction temperature inside the structure. All non-linear temperature dependences of the main MOSFET transistor parameters like threshold voltage V_{T0}, drain resistivity R_D and breakdown voltage V_{BR} are

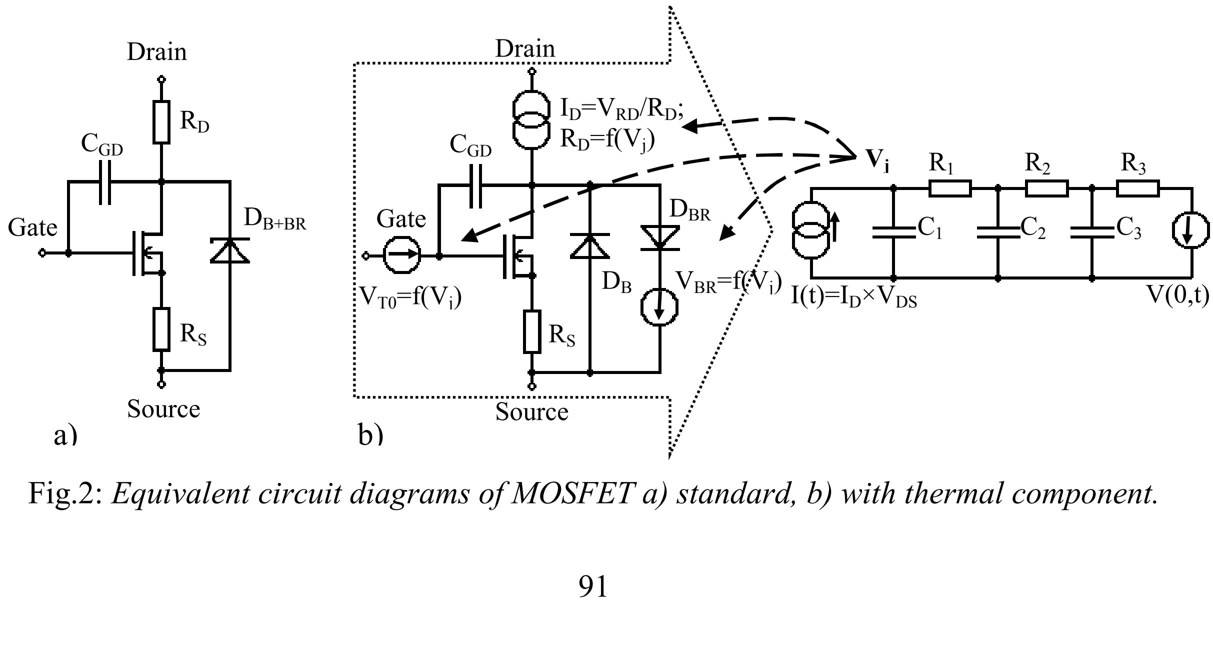


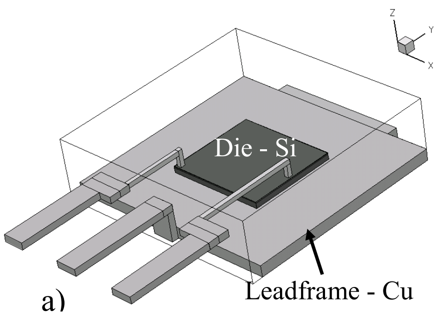
Fig.2: *Equivalent circuit diagrams of MOSFET a) standard, b) with thermal component.*

driven by the V_j node voltage using of the voltage controlled voltage source (VCVS) and voltage controlled current source (VCCS) [2].

The electrical equivalent RC network of the trench MOSFET thermal system in the DPAK2 package (Fig. 3a) was calculated from Eq.(1). Five RC elements $R_{1\text{-}5Si}$ - $C_{1\text{-}5Si}$ represent the silicon die part and $R_{5\text{-}7Cu}$ - $C_{6\text{-}7Cu}$ elements represent the copper leadframe part. The optional external heat sink RC part can be used for connected package on an external cooler. The coefficients of the thermal conductivity κ and thermal capacity c were taken from the Table 1 [3-4]. The temperature dependence of the thermal conductivity is dismissed for the RC network with constant element.

Table 1: *Thermal coefficients.*

	T(K)	300	400	500
	c(J/(K cm^{-3}))	*κ(W/cmK)*		
Si	1.63	1.55	1.09	0.82
Cu	3.42	4.01	4.00	3.98



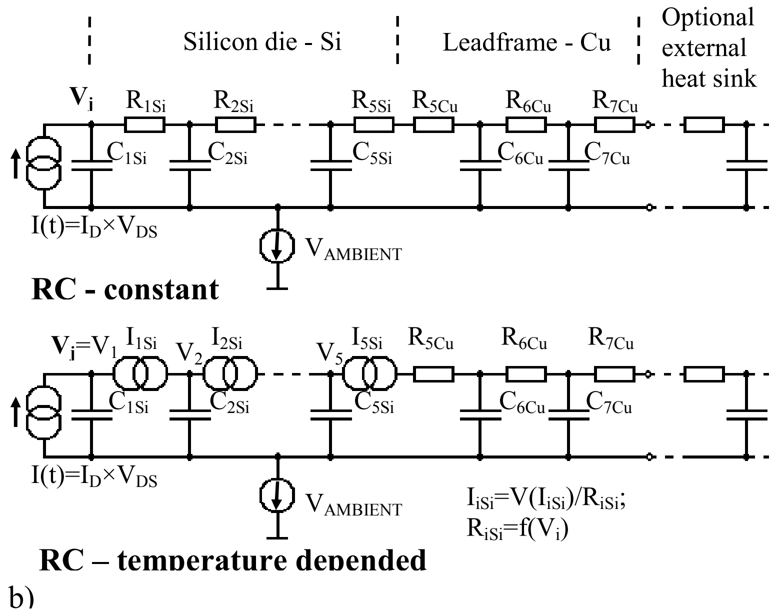


Fig.3: *a) DPAK2 package, b) thermal equivalent circuit diagrams for power MOSFET.*

Due to the strong temperature dependence of the thermal conductivity, mainly in the silicon, a mismatch can occur between the temperature flow in the structure and current flow in the equivalent circuit. Therefore the RC network with temperature depended resistances was designed. The temperature depended resistances were replaced only for the silicon die part. The resistances are created

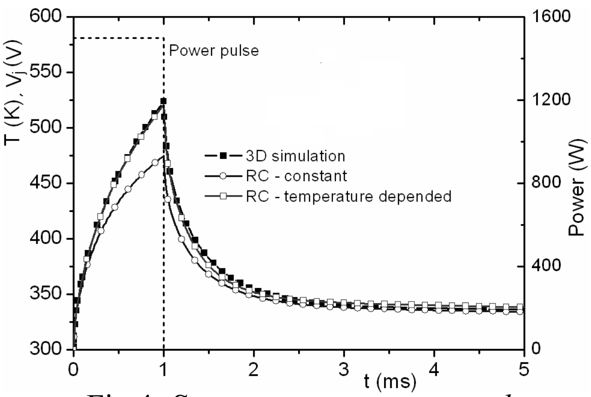


Fig.4: *Structure temperature and RC network voltage V_j.*

with a voltage controlled current source (VCCS). The driving voltage function is set according to the temperature depended thermal resistivity function.

Fig. 4 shows the junction temperature characteristics inside the power MOSFET and the V_j node voltages for both equivalent thermal circuits during 1 ms pulse duration with 1.5 kW power. The temperature is extracted for the 3D thermal simulation of the DPAK2 using the Sentaurus Devise tool [4]. The difference for constant temperature RC network is caused by neglected temperature dependence of the thermal conductivity. The very good agreement between 3D simulation and the originally proposed temperature depended RC network behavior is clearly seen.

4. Conclusions

The new SPICE-like simulation models which contain a dynamic link between electrical and thermal component descriptions were presented. Two thermal equivalent circuit diagrams were designed for the power MOSFET. Due to the strong temperature dependence of the thermal conductivity, the constant RC network exhibits a different behavior then thermal system. The very good agreement for temperature depended RC network confirms the validity of the designed model.

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