Electro-Thermal Modelling and Simulation of a Power-MOSFET

1. INTRODUCTION

Optimisation of power electronic's thermal system is today as well important as electrical optimisation. Power electronics engineer need to know electrical and thermal properties of power electronics system, as well as their interaction. Until last few years no low- and mid-range circuit simulators are reported with possibilities of providing electro-thermal simulation, based on relatively simple electro-thermal models of power electronics components. Simulation was performed at fixed, static temperature. But this is not enough for good predicting of power semiconductor's behaviour. Many properties of semiconductors are strongly temperature dependent, thus making the temperature one of the critical parameters for system's behaviour.

For the power semiconductor's long lifetime and reliability both maximum junction temperature and temperature cycling are important. Junction temperature influences on many component parameters and exceeding of maximum junction temperature can lead to fatal errors or permanent damage of the component. Strong temperature cycling of power semiconductor can lead to mechanical stress in the component, especially at solder and bond connections. Some authors report strongly nonlinear dependence of component's lifetime on temperature cycling. Until the introduction of electro-thermal simulation, calculation of junction temperature was performed by approximate method, i.e. using transient thermal impedance diagram (TTIC or \( z_{th} \)) given in catalogues (data sheets). The use of electro-thermal models of power semiconductor enables fast and accurate simulation of power electronics system behaviour. Each power semiconductor can be electro-thermally modelled, but power MOSFET was chosen because some of it's parameters are strongly temperature dependent and extremely important for MOSFET's behaviour in power electronics circuit.

2. BASIC IDEA OF ELECTRO-THERMAL MODELLING

Electrical models of all power semiconductors, from simple to complicated ones, are well defined and used in circuit simulators for power electronics. In equations describing the semiconductor's behaviour fixed junction's temperature \( T_J \) should be replaced in some way with variable \( T_J(t) \) junction temperature obtained as a response on semiconductor's power loading. Thermal models of power semiconductor exist in the variety of forms and complexity. It was shown that even simple ladder network (RC) thermal models of power semiconductors based on electro-thermal analogy, can give satisfactory result if properly used [1]. Figure 1 shows the basic idea of electro-thermal modelling. Modified electrical model of power semiconductor is used with some parameters temperature dependent. In power MOSFET case, these are: drain resistance \( R_D(T_J) \), threshold voltage \( U_{TH}(T_J) \) and electron mobility in channel region \( \mu(T_J) \).

Ladder network thermal model, consisting of several \((R_{th}, C_{th})\) pairs is used for calculation of junction temperature \( T_J \). Input for this network is instantaneous power \( p(t) \) dissipated in power MOSFET and calculated as a product of MOSFET's instantaneous current and voltage \((I_D \cdot U_{DS})\), obtained by means of electrical model. Direct interaction of electrical and thermal system can be seen.
It is important to say that great care should be given to the parameters of the thermal model. For simple structures, thermal equivalent elements ($R_{th}$, $C_{th}$) can be obtained from the physical structure [2], but much better way is measurement of TTIC curve and identification of equivalent thermal parameters [3].

3. ELECTRO-THERMAL MODEL OF POWER MOSFET

To develop the electro-thermal model an electric simulator from the SPICE programme family was used. It is an IsSpice4 software package [4].

The electric model of MOSFET used to calculate the time course of voltage and current, respectively instantaneous power, has a subcircuit structure, Figure 2.a), [5].

Static characteristics in the linear region and in the saturation region were modelled with an in-built model of the signal MOSFET M1, respectively model LEVEL=3. This model takes into consideration the short and narrow channel effects on the electron mobility in the channel and on threshold voltage.

Dynamic characteristics of power MOSFET were modelled with a network of a passive components and voltage-controlled switches.

Temperature dependence of the electric model parameters was reduced to electron mobility in channel $\mu$, drain resistance $R_D$, threshold voltage $U_{TH}$ and breakdown voltage $U_BR(DSS)$. As in the existing SPICE model LEVEL=3 temperature is not a system variable, a program command has excluded the in-built temperature dependences of the model's electric parameters.

The system's thermal model is the known electric ladder network, Figure 2.b). Applying this model requires a knowledge of conditions for the existence and of the limits on the use of power MOSFET's transient thermal impedance [1]. A current-dependent voltage source $H_1$ and voltage-dependent voltage source $E_1$ convert the time course of current $i_D(t)$ and voltage $U_{DS}(t)$ to the instantaneous power $p(t)$. Current of the voltage-dependent current source $G_1$ is analogous to the instantaneous power.

The dependence of electron mobility in the channel on temperature $T$ is described by equation [6]:

$$\mu T = \mu(T_{ref}) \left( \frac{T_{ref}}{T} \right)$$

where:

$T_{ref}$ is referential temperature
$\mu$ is constant between 1.5 i 2

The model of temperature-dependence electron mobility was incorporated by using nonlinear current sources $B_1$ i $B_2$. Current from source $B_1$ is equal to the product of current through MOSFET M1 and factor $(T_{ref}/T)^{\mu}$. Current of the current source $B_2$ is equal to the current through MOSFET M1 and it has opposite direction. $T_{ref}$ and $m$ are incorporated in current source $B_1$ as constants. $T$ is the controlling variable of the current source and analogous to the input voltage in the model of the semiconductor thermal system.

Temperature dependence of drain resistance is described by equation [7]:

$$R_D(T) = R_D(T_{ref}) \left( 1 + \alpha \left( \frac{T}{100} - T_{ref} \right) \right)$$

$\alpha$ is a constant between 0,6 and 0,9. The model of temperature-dependence drain resistance was incorporated by using a nonlinear B-source. Output resistance of this source is function of input voltage [4]. This source was, as resistance $R_D(T)$, serially connected with the model of a signal MOSFET M1.
$T_{\text{ref}}$, $\alpha$ and $R_D(T_{\text{ref}})$ were incorporated in the source as constants. $T$ is the controlling variable of this source and is analogous to the input voltage in the model of semiconductor’s thermal system.

Temperature dependence of threshold voltage is described by equation (3):

$$U_{\text{TH}}(T) = U_{\text{TH}}(T_{\text{ref}}) - m_1(T - T_{\text{ref}})$$

$m_1$ is constant between 0.5 and 4 mV/K. The model of temperature-dependence threshold voltage was incorporated by using a nonlinear voltage-dependent voltage source $B_3$. Its value is described by equation:

$$U_{B3} = m_1(T - T_{\text{ref}})$$

$m_1$ and $T_{\text{ref}}$ were incorporated in voltage source $B_3$ as constants. $T$ is the controlling variable of this voltage source and is analogous to the input voltage in the model of semiconductor’s thermal system.

Temperature dependence of breakdown voltage is described by equation (6):

$$U_{\text{BR}(DSS)}(T) = U_{\text{BR}(DSS)}(T_{\text{ref}}) + T_{C1}(T - T_{\text{ref}}) + T_{C2}(T - T_{\text{ref}})^2$$

$T_{C1}$ and $T_{C2}$ are temperature coefficients. The model of temperature-dependence breakdown voltage was incorporated by using a nonlinear voltage-dependent voltage source $B_4$ and diode $D_{\text{PROB}}$. At room temperature, the voltage of voltage source $B_4$ corresponds to the breakdown voltage reduced by the voltage drop at a forward polarized diode $D_{\text{PROB}}$. $T_{\text{ref}}$, $T_{C1}$ and $T_{C2}$ were incorporated in voltage source $B_4$ as constants. $T$ is the controlling variable of the voltage source and is analogous to the input voltage in the model of semiconductor’s thermal system.
4. EXTRACTION OF MODEL PARAMETERS

Parameters of the electro-thermal model of power MOSFET are parameters of the electric and those of the thermal model.

The electric model has these parameters:
- parameters of static characteristics
- parameters short and narrow channel effects
- parameters of temperature dependence
- parameters of dynamic characteristics.

Recently, for use in SPICE family simulators some power MOSFET manufacturers provide in their catalogues parameters of static characteristics as well as short and narrow channel effect parameters, namely model LEVEL=3 parameters. If not given, they should be calculated from either measured or catalogue characteristics of a MOSFET.

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The static characteristic parameters are current coefficient β(Kp), threshold voltage \( U_{TH} \), mobility modulation parameter \( \theta \), parasitic total resistances \( R_D \), \( R_S \) and \( R_G \). The values of these parameters are determined from transfer characteristic \( I_D = f(U_{GS}) \) in the linear region or in the saturation region [5].

Most parameters of the short and narrow channel effects are roughly equal to zero due to the vertical structure of power MOSFET. The body-effect parameter γ is equal to zero because of the short circuit between the source and bulk of the power MOSFET. The static feedback on threshold voltage parameter γ is equal to zero because of the expansion of depleted area beneath the drain into drift area instead into channel. Field factor in saturation \( \eta \) is equal to zero because of the assumption that the saturation of current \( I_D \) is caused by the saturation of drift velocity of carriers, not by pinch-off. The maximum drift velocity of carriers \( v_{max} \) is determined by comparing simulated output characteristic with catalogue output characteristic [9]. Width effect on threshold voltage parameter \( \alpha \) is also determined by comparing the simulated transfer characteristic with the catalogue or measured transfer characteristic. In determining simulated transfer characteristics, a model of conduction power losses with all predetermined parameter values is used. Parameter values are modified until a satisfactory agreement between simulated and catalogue characteristics is obtained.

The parameters of temperature dependence are coefficients in the voltage-dependent voltage and voltage-dependent current sources from Figure 2.

The value of coefficient \( m_1 \) from the model of the temperature dependence of threshold voltage is equal to the slant of the catalogue dependence curve of threshold voltage on temperature [10].

The value of coefficient \( m \) from the model of temperature dependence of drain resistance is determined by comparing a simulated drain resistance characteristic with a catalogue characteristic of the same type. The value of the coefficient is modified until a satisfactory agreement between the simulated and measured transfer characteristics is obtained. At reference temperature drain resistance \( R_{DS(on)}(T_{ref}) \) is equal to the predetermined serial resistance \( R_D \).

The value of coefficient \( m \) from the model of electron mobility temperature dependence is determined only after coefficient values the remaining model of parameter temperature dependencies have been found. Coefficient \( m \) is determined by comparing the simulated transfer characteristic with the measured transfer characteristic. As the initial coefficient for \( m \) empirical values between 1.5–2 are taken.

The value of \( U_{BR(DSS)}(T_{ref}) \) from the model of temperature-dependence breakdown voltage is the catalogue data. Coefficient values \( T_C1 \) and \( T_C2 \) for this model are calculated from the catalogue curve slant for the dependence of breakdown voltage \( U_{BR(DSS)} \) on temperature.

Dynamic characteristic parameters are parasitic inductances and parameters of the model of parasitic nonlinear capacities. The values used as parasitic inductance \( L_S \), \( L_D \) and \( L_G \) are mostly empirical. To calculate parameter values of capacity models \( C_{GD}, C_{GS} \) and \( C_{DS} \) one uses catalogue curves of the dependence of input capacity \( C_{GS} \), output capacity \( C_{DS} \) and transfer capacity \( C_{GS} \) on voltages between source, drain and gate. Also needed are curves at positive and negative voltage values \( U_{DG} \). Parameters of the thermal system model are equivalent electric resistances and capacities from the electric model, Figure 2.b). In calculating the values of these resistances and capacities the numerical procedure [3] used involves either catalogue or measured curves of transient thermal impedance of a power MOSFET.

5. SIMULATION AND MEASUREMENT

A developed electro-thermal model was tested by simulating and measurement the behaviour of MOSFET under different operating conditions, short circuit, active operating region and different types of combined losses, consisting of switching and conduction losses. The most interesting operating conditions for testing model accuracy are combined losses. In order to enhance the influence of switching losses at relatively low frequencies (10
kHz), 7 kΩ gate resistance was added to slow down switching process. MOSFET was not kept fully opened during conduction interval, but with lowered gate voltage (near threshold voltage) MOSFET was held between saturation and active operating region. As a load, serial connection of resistance and inductance was used with freewheeling diode. Figure 3 illustrates the test assembly for simulations under combined losses condition.

Accuracy of simulation results depends on the electric and thermal models, their interaction, and on the accuracy with which their parameters have been determined. As the proof for the model and simulation accuracy, measurement method with independent temperature sensor should be used. As temperature indicator, TEMPFET was used, MOSFET with integrated overtemperature protection. Before the use, TEMPFET was calibrated to find out its overtemperature protection reaction temperature. This critical temperature 

$$T_{\text{crit}}$$

was find out repeatable and very stable ($T_{\text{crit}} = 170 °C$ at $T_{\text{AMB}} = 17 °C$). Also the TTIC (transient thermal impedance curve) for the device was measured. TTIC was measured with threshold voltage as TSEP and in active operation region during heating phase. This should give the worst case TTIC for examined TEMPFET. On the base of measured TTIC, appropriate thermal model of TEMPFET was build, as a simple, modified ladder RC model where parameters identified on the base of its TTIC. Measurements were done under same conditions as in simulation. The aim of simulation and measurement was to force TEMPFET to reach the critical temperature $T_{\text{crit}}$ when its overtemperature protection reacts.

Fig. 3 Scheme of the test assembly for combined losses simulation and measurement

The simulation and measurement was done for TEMPFET BTS131, at a circuit voltage $U_D = 40$ V, load inductance $L_1 = 1$ mH, load resistance $R_1 = 1.2$ Ω and gate resistance $R_G = 7$ kΩ. To facilitate parameter setting and changing, the electro-thermal model is shown by means of two subcircuits. Subcircuit X₁ is the electric and subcircuit X₂ is the thermal part of this model. With a voltage source $V_3 = 288$ K the referential temperature was simulated. Resistance $R_2 = 100$ MΩ helps convergence during the simulation.

Simulation results are shown in Figures 4 and 5 TEMPFET’s virtual junction temperature $T_J$ and sensor temperature $T_S$ were monitored. As the aim of simulation was to estimate the time interval needed for overtemperature protection work-out, time instant $t_{\text{SIMcrit}}$ at which $T_S$ reaches 170 °C (443 K) was requested result, $t_{\text{SIMcrit}} = 500$ ms. Why $T_S$ and not $T_J$ was taken into account when estimating overtemperature protection work-out time?

![Simulated characteristic TEMPFET's waveforms (current – 3, voltage – 2, power – 1) during two combined losses operating cycles using electro-thermal model](image)

![Temperature simulation results for combined losses operating conditions by use of the electro-thermal model. Note the overtemperature protection work-out time $t_{\text{SIMcrit}}$ at $T_S = 443$ K](image)
As TEMPFET’s temperature sensor is mounted on the silicon surface, not inside MOSFET’s structure, sensor’s temperature is averaged and delayed virtual junction temperature. Overtemperature protection is based on temperature sensor information, so sensor’s temperature $T_S$ should be used instead of virtual junction temperature $T_J$.

Power waveforms during experiment are not accurate due to the digital oscilloscope sampling nature, but the time instant of overtemperature protection work-out $t_{MEAScrit}$ can be clearly detected and measured, $t_{MEAScrit} = 560$ ms. This result is in excellent agreement with simulatively estimated $t_{SIMcrit}$ on Figure 5.

Such an agreement between simulated and measured results confirms that even simple thermal model, when properly implemented into electro-thermal model of power semiconductor, enables accurate electro-thermal simulation of power electronic circuits. As a consequence, such a thermal model of power MOSFET was implemented into SIMPLORER’s semiconductors library under development, as a part of collaboration with SIMEC GmbH.

6. CONCLUSION

An idea of power MOSFET’s electro-thermal modelling is described. By modification of built-in SPICE-like electrical model, adding simple ladder network model of MOSFET’s thermal behaviour, relatively simple and accurate electro-thermal model of power MOSFET is obtained. Such a model can be succesfully used in most standard electrical circuit simulators for determining semiconductor’s operating temperature during various operation cycles. Final verification was provided on the TEMPFET example, when overtemperature reaction time was measured and simulated for the same conditions. Good agreement of measured and simulated results confirms the expectations.

REFERENCES

Elektrotoplinsko modeliranje i simulacija učinskog MOSFET-a. Za postizanje što bolje optimizacije sklopa i sustava energetske elektronike danas se zahtijeva elektrotoplinska simulacija učinskih poluvodičkih sklopk. Za to su potrebni točni, no i presloženi elektrotoplinski modeli učinskih poluvodičkih sklopk, pogodni za primjenu u tržišno dostupnim simulatorima sklopa energetske elektronike. U članku je prikazana IsSpice realizacija elektrotoplinskog modela učinskog MOSFET-a. Model se sastoji od električkog i toplinskog dijela koji međusobno izmjenjuju vrijednost varijabli. Elektrotoplinski model ispitán je mjerenjem na stvarnom sklopu.

Ključne riječi: elektrotoplinska simulacija, modeliranje, učinski MOSFET

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