THE ESTIMATION OF SEMICONDUCTOR'S SILICON TEMPERATURE IN THE REAL OPERATING CONDITIONS

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Abstract Simple thermal model of power semiconductor can serve for estimation of semiconductor's silicon temperature by means of electrical circuit simulation. Accuracy of such an estimation procedure is proven on several examples of power semiconductor's operating conditions which can come out in reality. As a temperature sensor, power MOSFET with integrated temperature sensor was used. Reaction time of overtemperature protection was measured, and then simulated for the same operating conditions. Comparison of measured and simulated results shows acceptable accuracy of silicon temperature estimation procedure, if proposed suppositions are fulfilled.

Keywords. semiconductor's thermal model, semiconductor's silicon temperature, transient thermal impedance

INTRODUCTION

Thermal characterization of power electronic devices is today one of the most important problems in the design and utilization of power electronic converters and systems. The behavior and life-time of power electronic devices (BJT, IGBT, MOSFET, etc.) depends on semiconductor's stationary silicon temperature as well as on oscillations of silicon temperature. It is important to be able to predict semiconductor's silicon temperature (in continuation – silicon temperature) in the real operating conditions. Different methods exists to estimate the silicon temperature, but not all of them are appropriate for the real operating conditions of power electronic device. Basic methods are: electrical (via TSEP, Thermo-Sensitive Electrical Parameters), optical (the use of Infrared Microradiometer) and numerical methods (electrothermal simulation). Only numerical methods are promising for fast estimation of silicon temperature, because they can be implemented into existing computer aided design process.

There are several approaches in modeling semiconductor's thermal circuit, with different accuracy and complexity, having its own advantages and drawbacks. Semiconductor's thermal circuit can be modeled with 2D or 3D-FEM like methods, solving heat transfer differential equations and basic semiconductor differential equations. Very promising is Hefner's [1] approach using powerful SABER simulator, but requiring huge amount of disk and memory space. But for wider use in engineering praxis this approach is very time and money consuming. A method is required, that can easily be realized on a usual PC (today PENTIUM 166 MHz) with commercially available simulation software. A possible solution is the use of a simple electrical model of semiconductor's thermal circuit. This paper will describe the procedure of modeling the semiconductor's thermal circuit based on RC-ladder model and using SIMPLORER® software for simulation of silicon temperature in the real operating conditions.

In literature, the accuracy of simple electrical model for the estimation of silicon temperature is usually undervalued, but without concrete proofs. Certainly, the independent method of silicon temperature measurement is required for validation of simulation results. In this work, the TEMPFET® (MOSFET with integrated temperature sensor) is chosen for nondestructive measurement of silicon temperature in the real operating conditions. The results of silicon temperature measurement and simulation are compared and analyzed under different operating conditions.

TEMPERATURE SENSOR - TEMPFET®

TEMPFET® is relatively new power device [3] with built-in overvoltage and overtemperature protection, useful in medium to low switching speed applications (e.g. automotive industry). The simplified TEMPFET® structure is presented on Fig. 1. showing it's "chip-on-chip" approach. Temperature sensor chip is mounted on the top of power chip and fixed with electrically isolating epoxy, providing excellent thermal contact and maintaining good electrical isolation between the sensor and the power chip. The sensor chip senses the temperature of the power chip and shuts off gate drive if it reaches a critical temperature T_{crit}. Because of the "chip-on-chip" approach, there exists another thermal path, described later in thermal model with R_{thS} and C_{thS}, which is not included into classical RC ladder model of power semiconductor.
Before the experiment, TEMPFET® was calibrated in the temperature controlled oven to find out what is the

critical temperature T_{crit} at which it shuts down. Results of calibration were repeatable, showing clear result T_{crit}=170°C. As ambient temperature during experiment was T_{AMB} = 17°C, silicon overtemperature at which TEMPFET® should shut off is $\Delta T_J = T_{crit} - T_{AMB}$ = 153°C. In the experiment, TEMPFET® was loaded with short pulses of constant power and different amplitudes (from 100 to 340 W, higher then TEMPFET's maximum stationary dissipation) and with combined loading consisting of conduction and switching losses at high frequency, representing device's real operating conditions.

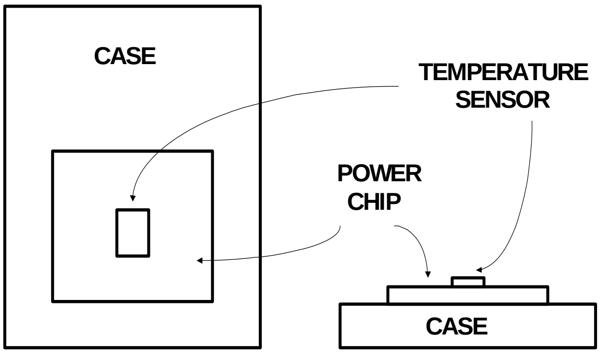

Fig. 1 Simplified TEMPFET's physical construction

MODELING THE SEMICONDUCTOR'S THERMAL CIRCUIT

It is well known that there is an analogy between the electrical and thermal circuits under certain conditions [2]. Semiconductor's thermal circuit can be modeled with thermal resistances and thermal capacitances (R_{th}, C_{th}). Two basic RC thermal models exist: chain and ladder model. Both models have the same step-response (with equivalent parameters) but internal node responses are different. Chain model can be used when only input and output values of a model are important. Ladder model is more physical-like. One can see the basic thermal building blocks in the model. From a ladder model an influence of the heatsink can easily be removed, but this procedure is not here in focus. Ladder model should be used when internal properties of thermal system are of interest, e.g. temperature of silicon-case interface or case-heatsink interface.

The temperature sensor of TEMPFET® can be modeled as a separate RC pair connected between the junction node and the ambient node (reference point), as shown on Fig.2. Thermal resistance of modeled temperature sensor R_{thS} is supposed to have high value (usually 100–1000 times greater than semiconductor's thermal resistance), meaning that only a small part of thermal energy dissipated in semiconductor is going through temperature sensor. The value of sensor's thermal capacitance C_{thS} can be estimated from sensor's construction parameters, or empirically, to obtain sensor's response time constant of approx. 10–20 ms.

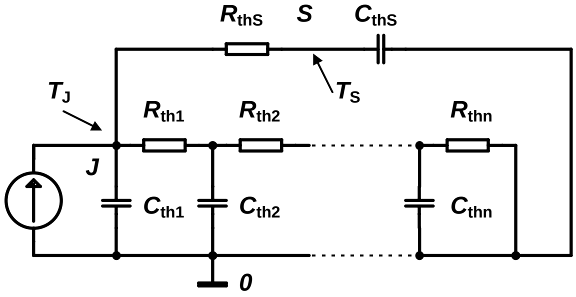

Fig. 2 The model of TEMPFET's thermal circuit

The main problem for an engineer in the application of semiconductor's RC thermal model is obtaining the appropriate (R_{th}, C_{th}) parameter values, because manufacturers are not publishing them in their catalogues (except few, e.g. SEMIKRON). Transient thermal impedance curve is published in every catalogue and it is the starting point for identification of (R_{th}, C_{th}) parameter values with appropriate software, e.g. THERM, developed at our University [4]. Input data are points of transient thermal impedance, which can be read-out from catalogue data or measured. Output data are (R_{th}, C_{th}) parameter values of a chain model, that are later converted into (R_{th}, C_{th}) parameter values of a ladder model.

SIMULATION OF SILICON TEMPERATURE

When the semiconductor's thermal model is chosen, and the model parameters are calculated, the next step is implementation of the power semiconductor's thermal model (RC ladder, Fig.2) into the circuit simulator. As a circuit simulator, the SIMPLORER® simulation package is used, enabling efficient and fast building of converter model as well as different complexity levels of power device models. Model of power device's thermal circuit can be easily implemented, using standard circuit simulator's components, requiring only power function $P_S(t)$ of the power developed in power device. There are different possibilities to obtain power function $P_S(t)$. One can model complex structure of a power converter and then use the calculated voltage $v_S(t)$ and current $i_S(t)$ of a power device to obtain power function $P_S(t)$. This option can be easily realized in SIMPLORER® . The accuracy of such an electro-thermal modeling approach depends on the accuracy of a power device model implemented in circuit simulator. To avoid the influence of power device model accuracy on the accuracy of silicon temperature simulation, in this work another approach for obtaining the power function $P_S(t)$ was chosen. During an experiment, real values of power device's voltage and current ($v_S(t)$, $i_S(t)$) were measured, and power function $P_S(t)$ was immediately calculated on digital oscilloscope. This calculated power function $P_S(t)$ was then used in circuit simulator as an input for thermal model. The idea of both approaches in obtaining the power function for electro-thermal simulation is presented on Fig. 3.

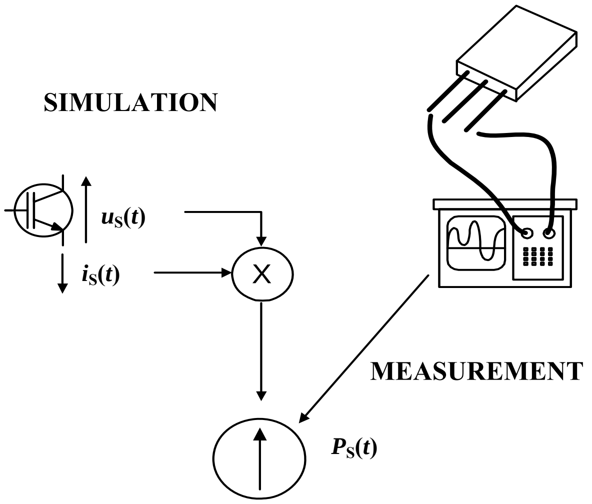

Fig. 3 Obtaining the power function $P_S(t)$ for electro-thermal simulation

Temperatures (overtemperatures) in semiconductor’s thermal system are calculated as node voltages of RC thermal model. One can easily calculate temperature of each point on RC thermal model (Fig.2). Node 0 (ground) represents the fixed ambient temperature T_{AMB}. Node J (junction) represents the point with the highest silicon temperature T_J. Node S (sensor) represents the sensor chip temperature T_S. It is obvious that sensor chip temperature follows the silicon temperature with some time delay, caused by the TEMPFET's structure. It is the sensor chip temperature T_S that turns TEMPFET off, not the silicon temperature T_J. So it is important to simulate sensor chip temperature T_S to correctly evaluate the experiment results.

RC parameters of TEMPFET's thermal model were obtained on the base of catalog transient thermal impedance curve (TTIC) and on the base of measured (with electrical method [5]) TTIC. It is interesting to investigate the usefulness of catalog TTIC for calculation of semiconductor's silicon temperature. Different modes of TEMPFET operation were simulated (same as in experiment) and reaction times of overtemperature protection were calculated as follows: t_{RSSM} – simulated reaction time of protection based on sensor chip temperature, t_{RSJM} – simulated reaction time of protection based on silicon (junction) temperature and on measured TTIC data, t_{RSJK} – simulated reaction time of protection based on silicon (junction) temperature and on catalogue TTIC data.

THE EXPERIMENT

Before the experiment, critical temperature T_{crit} for overtemperature protection of TEMPFET samples was calibrated. TEMPFET was fixed on copper water cooled heatsink to maintain constant referent ambient temperature T_{AMB} [6]. Measurement system was slightly

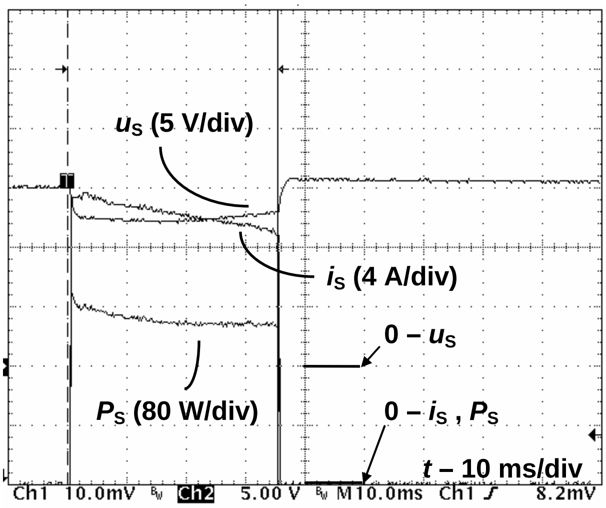

Fig. 4 Measurement of overtemperature protection reaction time for losses generated in active region of operation ($P_{S(AV)}$ = 223 W)

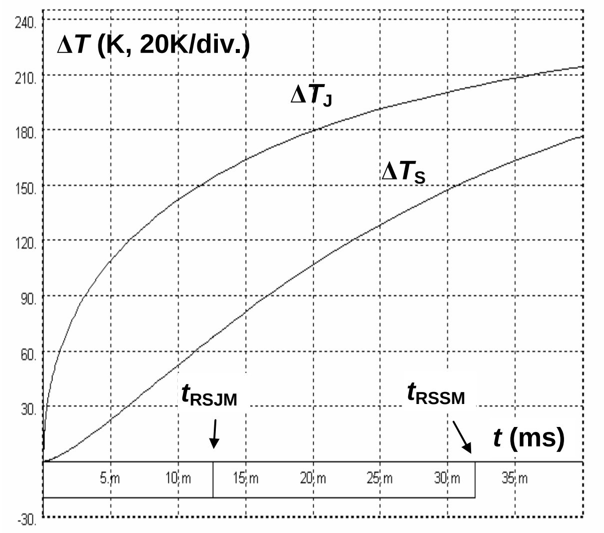

Fig. 5 Simulation of overtemperature protection reaction time for losses generated in active region of operation ($P_{S(AV)}$ = 223 W) based on T_J and T_S

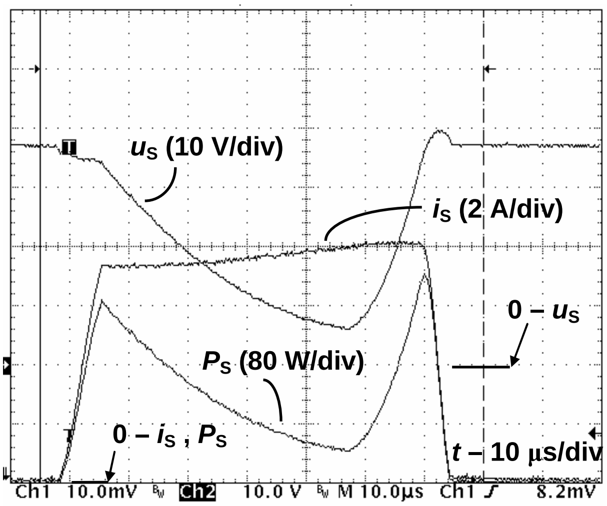

Fig. 6 Oscilloscope picture of one period of applied combined losses ($P_{S(AV)}$ = 78 W, f = 10 kHz)

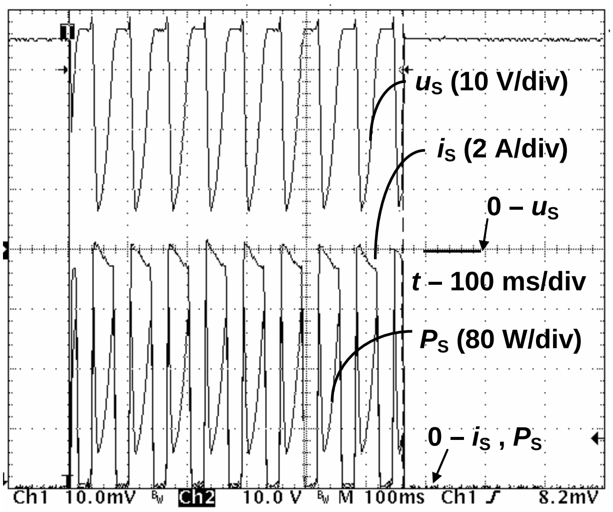

Fig. 7 Measurement of overtemperature protection reaction time for combined losses (from Fig. 6)

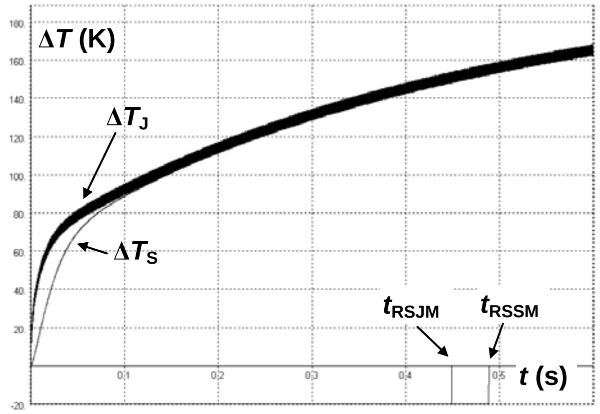

Fig. 8 Simulation of overtemperature protection reaction time for combined losses (from Fig. 6)
(t – 100 ms/div; ΔT – 20 K/div)

modified version of the transient thermal impedance measurement system [7], enabling the generation of different types of power dissipation on the power device.

Basically two types of power losses were used, active region losses (including short circuit case) and combined losses consisting of switching losses and conduction losses. Active region operation of power device is similar to short circuit condition, giving high dissipation level with medium voltage and current on power device. Different levels of dissipation P_S in active region were used in experiment resulting with different measured reaction times of overtemperature protection t_{RM}. An example of active region operation is shown on Fig. 4., with average value of losses P_S = 223 W. Reaction time of protection t_{RM} was measured by means of oscilloscope (cursors). In the case shown on Fig. 4. measured reaction time of protection was t_{RM} = 35.8 ms. Fig. 5. shows the equivalent simulation results. Silicon overtemperature ΔT_J and sensor chip overtemperature ΔT_S were simulated, clearly indicating time delay between two responses in up to 100 ms time region. In simulation, reaction time of protection was detected, when overtemperature ΔT reaches critical overtemperature value (in this case $\Delta T_{crit} = T_{crit} - T_{AMB}$ = 153°C).

Combined losses in TEMPFET were produced on frequency f = 10 kHz, with enhanced switching losses (higher gate resistance, R_G). An example of one period of combined losses used in experiment is shown on Fig.6. Measurement results of protection reaction time for combined losses are shown on Fig. 7. It should be noted that waveforms (u_S, i_S, P_S) are distorted because of oversampling in digital oscilloscope, but reaction time of protection can be clearly seen (between the cursors) as t_{RM} = 560 ms. On Fig. 8. the results of equivalent simulation are shown, again for two nodes, silicon and sensor. Oscillations of silicon temperature T_J can be seen, caused by pulsed dissipation in TEMPFET. Peak to peak amplitude of these oscillations is approximately 6°C. Protection reaction time based on T_J is defined in simulator as first point of reaching the critical temperature.

COMPARISON OF RESULTS

Table I presents the comparison results of measured data with simulated data. Measured protection reaction time t_{RM} (first row) is in an excellent agreement with simulated reaction time t_{RSSM} (second row) based on the sensor temperature and measured transient thermal impedance curve. The agreement between the results would surely be even better if the TEMPFET's structure was better described in thermal model. If the simulation of reaction time t_{RSJM} (third row) is based on the power chip temperature (not taking into account temperature sensor thermal circuit) the agreement between the results is not so good, especially for shorter reaction times. The simulation based on the catalogue data for transient thermal impedance (not self–measured) gives much worser agreement between the measured t_{RM} and simulated t_{RSJK} (fourth row) reaction times showing that catalogue data are too conservative in this case. For lower dissipation levels (P_S = 78 W), simulation based on catalog TTIC data showed no protection work-out. The reason for that fact is primary in the influence of contact thermal resistance between the case and the heatsink, which was not taken into account in this case.

TABLE I – Comparison of measured and simulated results of protection reaction time detection (t_R)

	COMBI-NED P = 78 W	**ACTIVE MODE P = 78 W**	**ACTIVE MODE P=118 W**	**ACTIVE MODE P=223 W**	**ACTIVE MODE P=332 W**
t_{RM}	560 ms	530 ms	170 ms	35,8 ms	15,4 ms
t_{RSSM}	495 ms	500 ms	156 ms	32 ms	19 ms
t_{RSJM}	450 ms	480 ms	140 ms	12,6 ms	4,4 ms
t_{RSJK}	*	*	23 ms	3,3 ms	1,2 ms

CONCLUSION

Semiconductor's silicon temperature can be estimated with acceptable accuracy by means of simple thermal model of power semiconductor in the real operating conditions, with conduction and switching losses taken into account. This was proven experimentally, with TEMPFET® as a power device and temperature sensor. That means that estimation of semiconductor's silicon temperature, needed in the power converter design process, can be included into usual simulation procedure by means of standard circuit simulator. Required supposition for such an electro–thermal simulation is having exact values of thermal model parameters (R_{th}, C_{th}). Unfortunately semiconductor manufacturers are not publishing this data in their catalogues. Published transient thermal impedance curves are often too conservative and own measurement of transient thermal impedance curve should be provided for good estimation of semiconductor's silicon temperature in the real operating conditions.

Acknowledgements

We wish to express special thanks to the people from SIMEC GmbH company, who helped us by ensuring latest version of SIMPLORER® simulation package, needed for successful electro-thermal simulation.

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