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Ivan Bahun, Neven Čobanov, Željko Jakopović

Real-Time Measurement of IGBT's Operating Temperature

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Original scientific paper

Temperature management and control are among the most critical functions in power electronic devices. Knowledge of power semiconductor's operating temperature is important for circuit design, as well as for converter control. Virtual junction temperature measurement or estimation is not an easy task, therefore designing the appropriate circuitry for virtual junction temperature in the real operating conditions not affecting regular circuit operation is a demanding task for engineers. The proposed method enables virtual junction temperature estimation based on the real-time measurement of semiconductor's quasi-threshold voltage using dedicated modified gate driver circuit.

Key words: IGBT, Measurement, Threshold voltage, Temperature sensitive electrical parameter

Mjerenje radne temperature IGBT-a u stvarnom vremenu. Upravljanje temperaturom je jedna od najkritičnijih funkcija kod učinskih poluvodičkih komponenata. Poznavanje radne temperature učinske poluvodičke sklopke vrlo je važno pri projektiranju sklopa, kao i za upravljanje učinskim pretvaračem. Mjerenje ili estimacija nadomjesne temperature silicija nije lagan zadatak, stoga je projektiranje odgovarajućeg sklopovlja za određivanje nadomjesne temperature silicija u stvarnim radnim uvjetima, koje ne utječe na normalan rad sklopa, vrlo zahtjevan inženjerski zadatak. Predložena metoda omogućava određivanje nadomjesne temperature silicija utemeljeno na mjerenju kvazi-napona praga u stvarnom vremenu pomoću posebno prilagođenog pobudnog stupnja IGBT-a.

Ključne riječi: IGBT, mjerenje, napon praga, temperaturno osjetljiv električki parametar

1 INTRODUCTION

Temperature management and control are among the most critical functions in power electronic devices. Operating temperature and thermal cycling can seriously affect device performance and reliability. In modern power converters, controlling the reliability of power semiconductor devices is becoming increasingly important. Just to name two important examples of modern power converter usage. Traction power converters (automotive and rail) as well as wind power converters are subject to large temperature oscillations during normal operation. Especially in wind power converters, due to the widely-varying and intermittent nature of the wind speed and the low converter modulation frequencies, severe reliability effects can occur because of emphasized thermal cycling. Therefore, it is important to be able to estimate the power semiconductor's temperature in real operating conditions. A better term is *virtual junction temperature*, the averaged temperature of active semiconductor, or even better, averaged temperature of the hottest active semiconductor part.

Two basic approaches to the operating temperature estimation can be identified. The first one is the development of an appropriate device thermal model, which can be implemented in real-time and used for estimation of temperature variations within the active region of the device (represented as virtual junction temperature). The complexity of developed thermal models varies from simple 1D models to complex 3D structures [1 - 6]. The second one is sensing the virtual junction temperature during converter operation by measuring the values of different *Temperature Sensitive Electrical Parameters* (TSEP) [7 - 10]. The latter is more complex for realization, but results in more accurate results.

The existing methods used nowadays to determine the instantaneous virtual junction temperature in single power devices cannot be used in converters operated in the field, due to the fact that they are basically quasi-static techniques. A solution has to be found for the measurement of power device instantaneous virtual junction temperature realizable under real operating conditions, and not affecting converter operation.

The switching behavior of power semiconductor devices has a large influence on the whole system's performance. Voltage and current peaks can be controlled by controlling the parameters of the gate driver circuit. Nowadays, modern, complex and powerful gate driver circuits are proposed, enabling full control of the switching process [11]. It is also advisable to implement the virtual junction temperature estimation possibility into the gate driver circuit [12]. The paper describes the new approach to the real-time virtual junction temperature estimation, based on the gate driver circuit modification and utilization.

2 TEMPERATURE SENSITIVE ELECTRICAL PARAMETERS (TSEPs)

Temperature sensitive electrical parameter of power semiconductor device is an electrical parameter that can be measured and has a defined temperature dependence. It serves for indirect methods of virtual junction temperature measurement. Not all possible TSEPs are appropriate for that purpose. Selection of TSEPs is based on several criteria [11]:

- *temperature sensitivity*; TSEPs have different values of temperature sensitivity, a greater TSEP temperature sensitivity gives better measurement results
- *measurement error*; the influence of non-thermal effects during measurement is different for each TSEP
- *linearity*; the linear relation between TSEP and temperature is a desired property, which is not always fulfilled
- *repeatability*; there should be no large scattering of TSEP values between different samples.

The choice of the most appropriate TSEP depends on the device under test type (DUT). The most important TSEPs are:

- voltage drop in on-state V_{DS} (V_{CE}) under small calibration current (at MOSFET this is $R_{DS(on)}$)
- gate threshold voltage V_{GSth} (V_{GEth}, V_{th})
- embedded diode on-state voltage V_{SD}
- avalanche voltage
- turn-on and turn-off delay times $t_{d,on}$, $t_{d,off}$
- maximum current slope at turn-on $\left(\frac{di_C}{dt}\right)_{MAX}$.

For MOS based devices (MOSFET and IGBT), past research [13] and literature overview [14] suggest gate threshold voltage V_{th} as the most appropriate TSEP for thermal resistance and transient thermal impedance measurements.

Good properties of threshold voltage as a TSEP are good temperature sensitivity ($\sim$ 10 mV/K related to $\sim$ 2 mV/K for $R_{DS(on)}$) and the fact that threshold voltage as a TSEP represents the hottest semiconductor part temperature (channel region).

A bad feature of threshold voltage as a TSEP is the fact that for a single device, threshold voltage depends on gate structure and concentration of carriers and therefore is not so reproducible for different samples of the same family. This could be an important drawback in individual application, but can be solved by simple referent measurement on one switch during converter testing.

The first step in using TSEPs as a temperature indicator is TSEP calibration at defined temperatures and deriving the calibration curve for the specified component. The obtained calibration curved should be used under actual operating conditions [15].

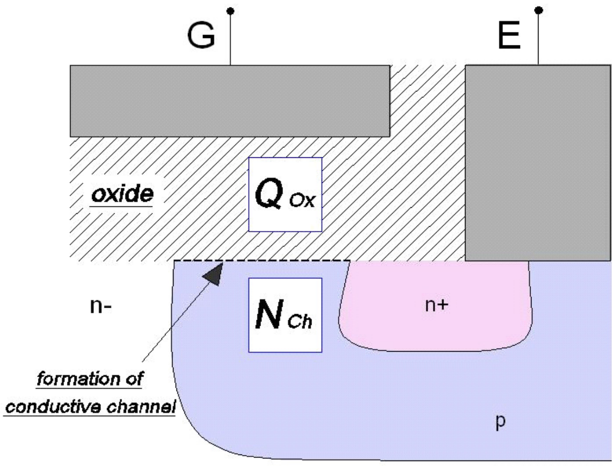


Fig. 1. Schematic depiction (n-channel device) of the basic MOS gate control structure, with an indication of the main factors defining the threshold-voltage value

3 IGBT THRESHOLD VOLTAGE - CHARACTERISTICS

MOSFET threshold voltage is well explained in literature [16]. IGBT has a very similar structure, but IGBT threshold voltage properties are not often elaborated. The same laws govern MOSFET and IGBT threshold voltage behavior, but due to the differences in technology temperature sensitivity is higher for IGBT ($\sim$ 10 mV/K) than for MOSFET ($\sim$ 5 mV/K).

The *threshold voltage* of MOSFET and IGBT is usually defined as the gate voltage where an inversion layer forms at the interface between the insulating layer (oxide) and the substrate (body) of the transistor. Historically, the gate voltage at which the electron density at the interface is the same as the holes density in the neutral bulk material is called the threshold voltage. Practically speaking, the threshold voltage is the voltage at which there are sufficient electrons in the inversion layer to make a low resistance conducting path between the MOSFET source and drain.

There is no clear definition of the current amplitude that should flow through the channel when the conducting path is formed. One should define this value on its own for calibration and measurement purposes.

Threshold voltage value is determined by many physical factors [16, 17]: the doping level in the channel region, the amount of fixed charge and surface energy states at the oxide–silicon interface, the oxide thickness, the presence of mobile ions in the gate oxide and the work function difference between the gate electrode and the silicon.

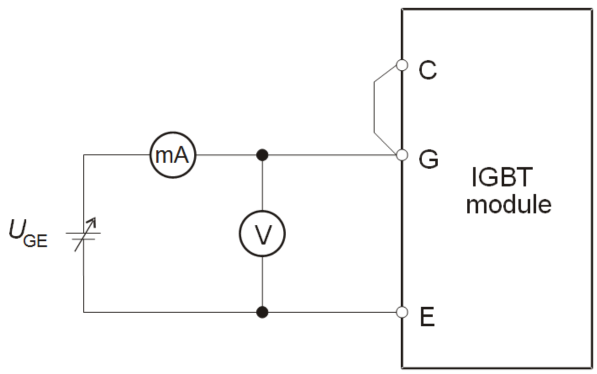


Fig. 2. Basic circuit for the calibration of the IGBT threshold voltage temperature dependence curve

A well known expression [16] defines the properties of threshold voltage

$$V_{th} = 2\psi + \frac{t_{ox}}{\varepsilon_{ox}}\sqrt{2\varepsilon_{Si}qN_{Ch}2\psi + \phi_{ms}} - \frac{t_{ox}}{\varepsilon_{ox}}Q_{ox}, \quad (1)$$

where t_{ox} is the thickness of the gate-oxide, ε_{ox} and ε_{Si} the dielectric constants of the oxide and silicon, respectively, q the elementary charge, N_{Ch} the doping of the channel region; ψ is the Fermi-potential, which accounts for the temperature dependence of V_{th} and ϕ_{ms} refers to the work function difference between the emitter metal electrode and the silicon; the last term describes the presence of mobile and fixed charge in the oxide and at the interface between the oxide and the silicon. Expression (1) indicates that the value of the threshold voltage can be varied intervening onto three fundamental parameters: the channel doping, N_{ch}, which also appears in the expression of the Fermi-potential [16], the oxide thickness, ε_{ox} , and the oxide charge, Q_{ox}.

Some of above parameters (e.g. the channel doping and the oxide charge) have the typical statistical variations of fabrication processes. For that reason the V_{th} value inevitably shows a spread, even among transistors belonging to the same production lot. This fact has consequences in the calibration procedure as well as in the practical application of the proposed method.

3.1 Threshold voltage temperature sensitivity

Temperature dependency of the threshold voltage is important for the proposed method. It can be obtained from the expression (1),

$$\frac{dV_{th}}{dT} = \frac{d\psi_B}{dT}\left(2 + \frac{1}{c_{ox}}\sqrt{\frac{\varepsilon_{Si}qN_A}{\psi_B}}\right), \quad (2)$$

with

$$\frac{d\psi_B}{dT} \approx \frac{1}{T}\left[\frac{E_g(0)}{2q} - |\psi_B|\right], \quad (3)$$

where ψ_B is the potential difference between the Fermi level and the intrinsic Fermi level, N_A the doping density, and $E_g(0)$ the band-gap energy at $T = 0$ K. This predicts a decrease of V_{th} with increasing temperature by 8.6 mV/K for certain IGBT device [17]. This is also the typical value of threshold voltage temperature sensitivity in previous experiments [13].

3.2 Threshold voltage temperature dependence-calibration

For the proper use of threshold voltage as a TSEP, appropriate calibration procedure should be implemented, resulting in derivation of calibration curves for the specified components in the temperature range of interest (20 − 125° C).

Figure 2 shows the circuit for the calibration of the threshold voltage temperature dependence curve.

IGBT module is placed on the temperature controlled board, maintaining referent temperature in the temperature range of interest.V_{GE} voltage is varied until a channel is formed and the defined amplitude of I_C calibration current is established (range from 1 mA to 100 mA). Then, the measured V_{GE} represents the threshold voltage V_{th} at the referent temperature.

Calibration measurements were performed on various IGBT samples resulting in interesting results.

Temperature dependence of the threshold voltage is measured on 4 *different samples of the same IGBT type* with typical results (Fig.3). Practically the same temperature sensitivity coefficient $k_T = -9.5$ mV/K can be noticed in all samples. The nominal value (at room temperature) of threshold voltage V_{th0} differs in the range of 0.2 V between the samples.

Sometimes the calibration curves have an excellent agreement between different samples of the same IGBT

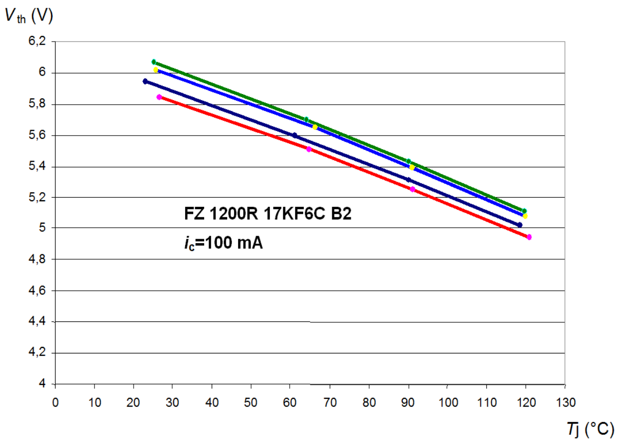


Fig. 3. IGBT threshold voltage temperature dependence calibration curves for different samples of the same IGBT type (typical results)

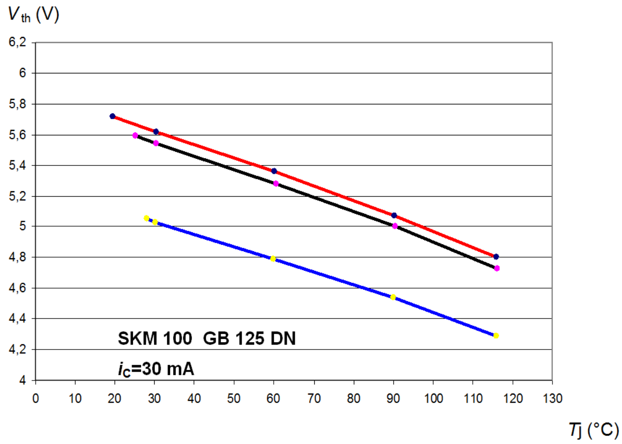


Fig. 5. IGBT threshold voltage temperature dependence calibration curves for different samples of the same IGBT type (bad agreement)

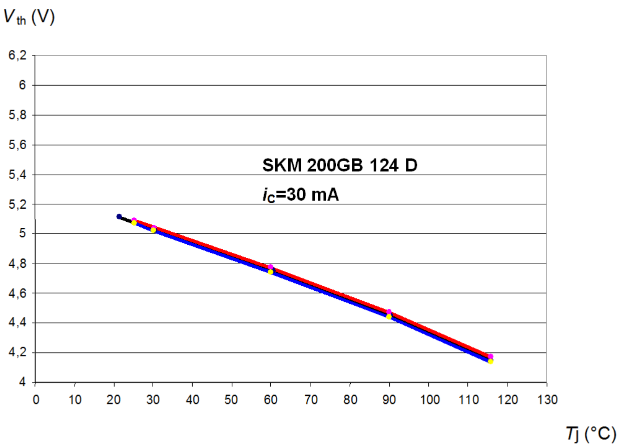


Fig. 4. IGBT threshold voltage temperature dependence calibration curves for different samples of the same IGBT type (good agreement)

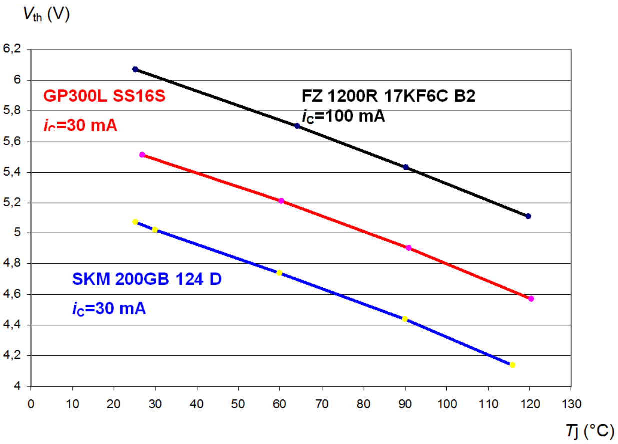


Fig. 6. IGBT threshold voltage temperature dependence calibration curves for different IGBT type and manufacturer samples (typical results)

type (Fig.4) and there are also cases when results scatter significantly between the samples (Fig.5).

When different IGBT samples from different manufacturers were calibrated (under different calibration currents), threshold voltage temperature calibration curves showed excellent agreement in temperature sensitivity coefficient k_T, but nominal threshold voltage V_{th0} differs between the samples (Fig.6).

Threshold voltage temperature dependence curves were measured on IGBT modules and small cases (TO 220, TO 247) IGBTs [13]. The typical value of temperature sensitivity coefficient k_T is $-10\,\text{mV/K}$ for IGBT modules and $k_T \sim -8\,\text{mV/K}$ for small cases IGBTs. The cause for difference in temperature sensitivity coefficient values between two classes of IGBTs is semiconductor device technology. Nominal threshold voltage V_{th0} values differ significantly between the samples.

For a successful practical application of threshold voltage as a TSEP for on-line temperature measurement, temperature sensitivity coefficient k_T should be measured firstly on a representative sample of used IGBT class. For each other IGBT sample used for on-line temperature measurement, only one measurement of nominal threshold voltage V_{th0} value at room temperature is sufficient.

In the temperature region of interest, the threshold voltage temperature dependence is obviously linear. When temperature sensitivity coefficient k_T and nominal threshold voltage V_{th0} are known for each device under test (DUT), a simple expression enables interpolation of semiconductor virtual junction temperature T_J on the base of the measured threshold voltage V_{thM}

$$V_{thM}(T_J) = V_{th0} - k_T(T_J - T_0). \quad (4)$$

Proper threshold voltage application as a TSEP requires that, when used for indirect temperature measurement, threshold voltage is measured under the same conditions during calibration and measurement phase. Therefore, proposed measurement method shall require a dedicated, slightly modified threshold voltage calibration procedure, but the fundamental properties of the threshold voltage, its temperature dependence and temperature sensitivity coefficient remain the same.

4 THRESHOLD VOLTAGE MEASUREMENT UNDER REAL OPERATING CONDITIONS

Threshold voltage measurement (for MOSFET and IGBT) is a very sensitive procedure, because it includes switching in the gate control circuit. Figure 7 shows basic circuit for threshold voltage measurement used for transient temperature response measurement [15], not for the measurement under real operating conditions. Only one switch is required, but in a very sensitive part of the circuit. This determines the careful approach to the circuit project. Threshold voltage is measured during the measurement phase, when defined measurement (threshold) current I_M flows through the DUT (*Device Under Test*). Another phase is the heating phase, when DUT is heated with defined losses (conduction, switching or combined). Switching between both phases should be fast, but without non-thermal transients, which is extremely hard to obtain. This is the reason why threshold voltage measurement under real operating conditions is not a standard method.

There were attempts to realize threshold voltage measurements with DUT heating pulses similar to those obtained under real operating conditions (conduction and switching losses) [18], but the experiment required too many modifications to be implemented in the normal converter circuit. There are no known realized methods using standard threshold voltage measurement under real operating conditions of standard power electronic circuit, even a simple one as a chopper. A new original solution has to be found.

5 USING QUASI-THRESHOLD VOLTAGE FOR REAL OPERATING CONDITIONS MEASUREMENTS

As mentioned in the introduction, modern gate driver circuits have advanced possibilities of the full switching process control. Also, measurement capabilities are possible to be implemented. The idea is to find an appropriate

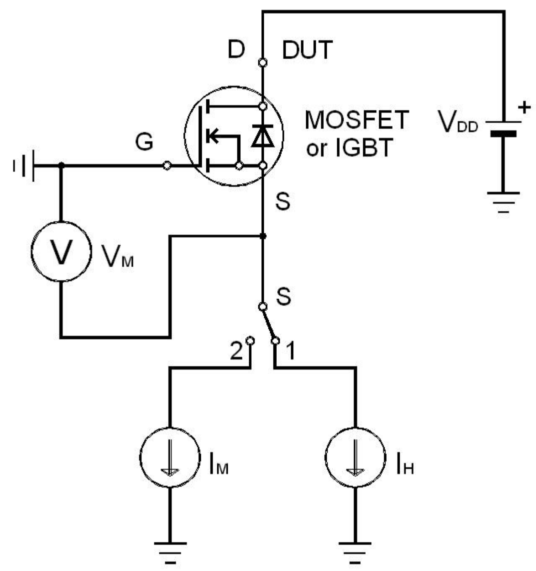


Fig. 7. Basic electrical circuit for threshold voltage measurement during transient temperature response measurements

phenomenon, representing the threshold voltage, which is possible to be measured under real operating conditions. During certain experiments in the past, a parasitic waveform in the emitter circuit was identified, representing the start of a collector current flow. Further investigation of this phenomenon enabled the development of a gate driver circuit, capable of semiconductor virtual junction temperature estimation under real operating conditions.

5.1 The quasi-threshold voltage concept

Figure 9 represents the phenomenon, representing the threshold voltage, not being exactly the threshold voltage, therefore called the quasi-threshold voltage. At the very beginning of collector current rise i_C, a small but measurable voltage $v_{L\sigma E}$is measured on the parasitic inductance $L_{\sigma E}$. Because of practical reasons, this voltage is inverted on the figures.

It is not the amplitude of this voltage that is important, but the exact moment of its appearance. This moment is detected by a sensitive comparator, as shown in Fig. 10. The signal from the comparator v_{CmpE} initiates gate voltage $v_{GE'}$ measurement. Voltage $v_{GE'}$ measured at the moment labeled T in Fig. 9 and 10, represents the threshold voltage v_{Th}, Fig. 11. This threshold voltage is measured in a non-standard way, therefore we called it the quasi-threshold voltage v_{QTh}.

5.2 The experiment power circuit

The power electronic circuit for the experiment was realized as a simple buck converter with a highly inductive

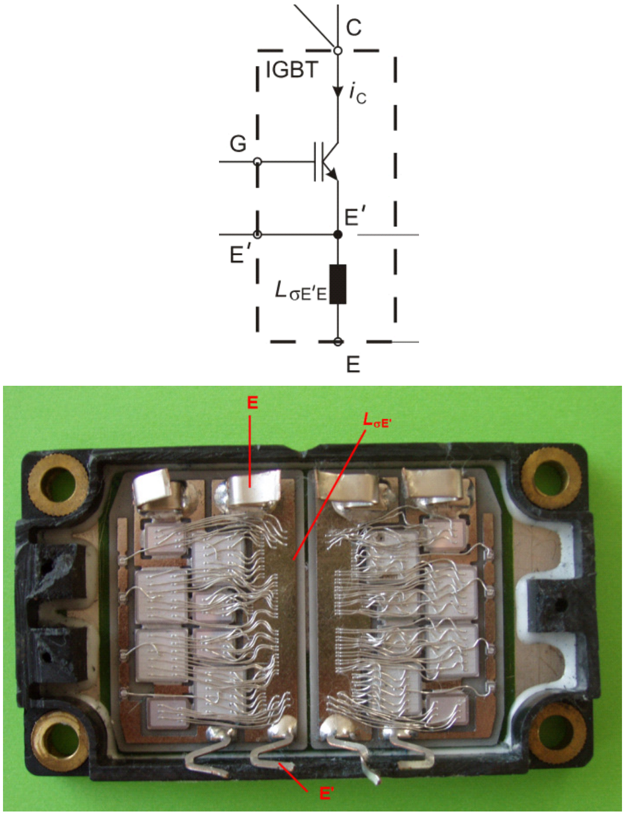


Fig. 8. The assumption of the method is that DUT is a component with existing parasitic inductance $v_{L\sigma E}$ between the emitter control and power connections E' and E, as represented in Fig. 8. This is always the case with large power IGBT (and MOSFET) power modules

load, Fig. 12 a). *Two-pulse method* was chosen for DUT loading, Fig. 12 b). This way of power loading causes minimal DUT temperature rise during the load current I_L rise. DUT first pulse on-time is long enough for the load current to reach the desired value during the first power pulse and small enough not to cause a significant temperature rise of the temperature controlled plate. The semiconductor temperature is assumed to be equal to the controlled plate temperature.

The quasi-threshold measurement is made at the beginning of the second power pulse, when the load current has reached its desired value.

As a DUT for real operating conditions temperature measurements, FUJI FZ 1200R 17KF6C B2 IGBT was used.

5.3 Quasi-threshold voltage calibration

The real operation conditions measurement requires appropriate quasi-threshold voltage calibration, under the same conditions as in the operation. As the quasi-threshold

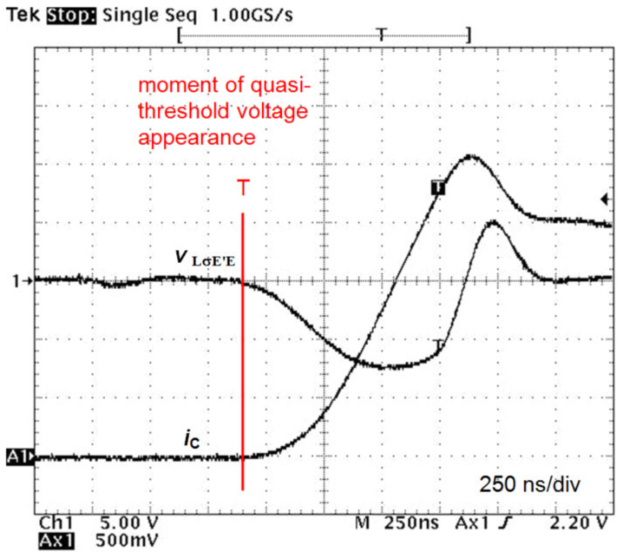


Fig. 9. Waveforms of collector current (i_C, 250 A/div) and parasitic inductance voltage ($-v_{L\sigma E}$, 2 V/div) during IGBT turn-on phase, T marks the moment of quasi-threshold voltage appearance

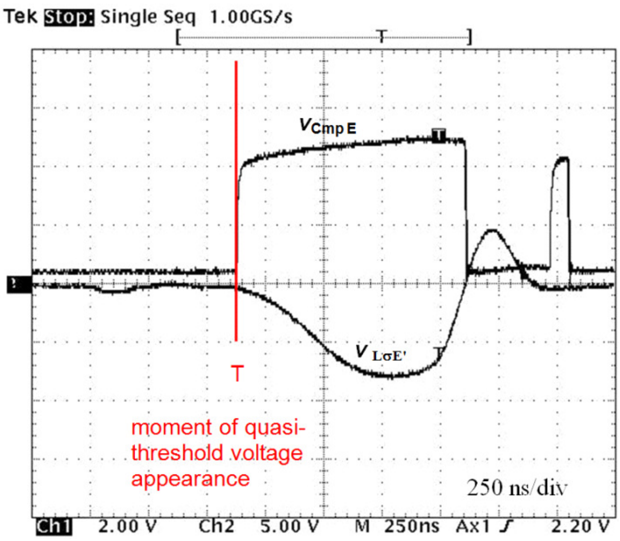


Fig. 10. Waveforms of parasitic inductance voltage ($-v_{L\sigma E}$, 2 V/div) and comparator signal (v_{CmpE}, 5 V/div) detecting the very beginning of collector current rise, T marks the moment of quasi-threshold voltage appearance

voltage temperature sensitivity is expected to have the same properties as classic threshold voltage, calibration in only two temperature points is chosen, at room temperature $T_0 = 19.1°$ C and high temperature $T_M = 120.5°$ C. At both temperature points, using the two pulse method, quasi-threshold voltage was measured. Stationary temper-

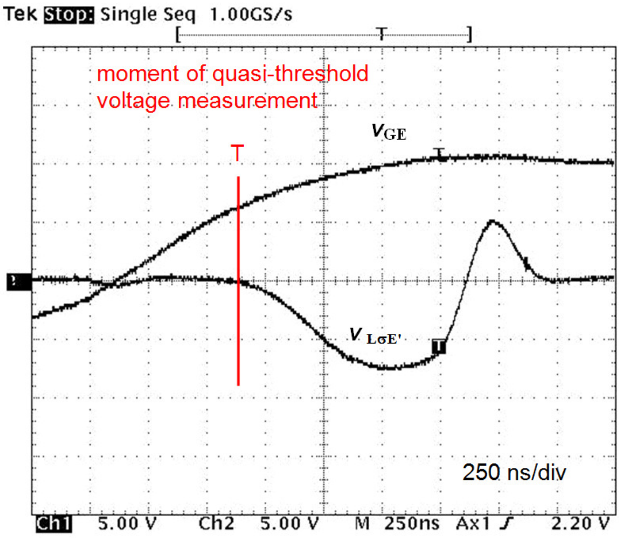


Fig. 11. Waveforms of parasitic inductance voltage ($-v_{L\sigma E}$, 2 V/div) and IGBT gate voltage ($v_{GE'}$, 5 V/div), T marks the moment of quasi-threshold voltage v_{QTh} measurement

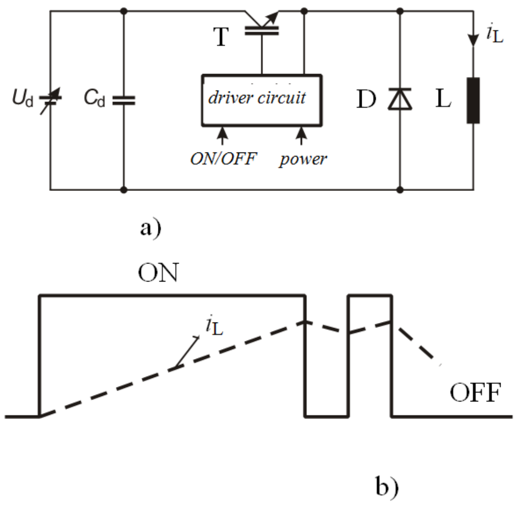


Fig. 12. A simple buck converter circuit with inductive load was used for the experiment; schematic a) and typical waveforms for two pulse method b)

ature of the controlled board was measured with thermocouples and quasi-threshold voltage was measured in the first phase with a digital scope, not with modified gate driver circuitry. The signal from the comparator is used as trigger for voltage measurement. Figure 13 a) and b) show calibration measurement results for two temperature points, resulting in temperature sensitivity coefficient for DUT, $k_T = -9.2\,\text{mV/K}$. The nominal quasi-threshold voltage V_{Qth0} at room temperature has a value

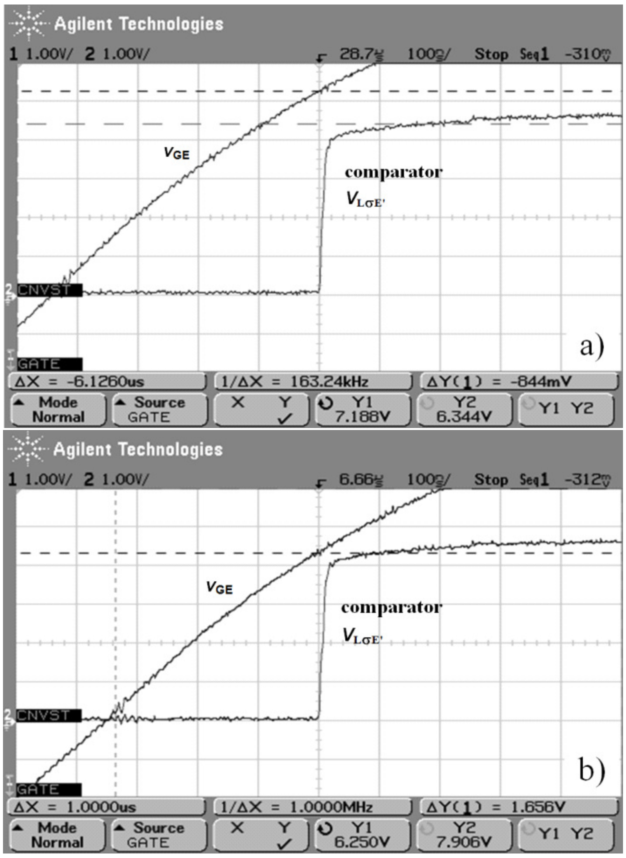


Fig. 13. Quasi-threshold voltage calibration at two temperature points using the two pulse method and a digital scope; a) at room temperature $T_0 = 19.1°\,C$ and b) at high temperature $T_M = 120.5°\,C$

of $V_{Qth0} = 7.188\,\text{V}$, at high temperature $T_M = 120.5°\,\text{C}$ quasi-threshold voltage $V_{QthM} = 6.250\,\text{V}$, resulting in a difference of $\Delta V_{Th} = 0.938\,\text{V}$. If the quasi-threshold voltage in the same two temperature points is measured with a modified gate driver circuit instead of a scope, a slightly different voltage difference is obtained, $\Delta V_{Th}^{'} = 0.888\,\text{V}$. The appropriate temperature sensitivity coefficient is $k_T^{'} = -8.76\,\text{mV/K}$. As real operation measurements are to be conducted with a modified gate driver circuit, calibration results taken with the modified gate driver circuit should be used as a reference point. The oscilloscope is not as accurate as dedicated gate driver circuitry.

5.4 Accuracy of quasi-threshold voltage method

During testing measurements, it was noticed that the maximum induced voltage on parasitic inductance $L_{\sigma E}$ gets larger with a larger load current. For the proposed method it is not the amplitude of the induced voltage that is important, but the moment when the induced voltage starts. The accuracy of the method was checked by comparing 2 quasi-threshold voltage measurements on the same DUT temperature, but with 2 different load current I_C amplitudes (250 A and 1000 A). Figure 14 represents this comparison. The time interval between voltage v_{GE} passing through zero and the reaction time of the comparator is the same for different load current amplitudes, which means that the captured quasi-threshold voltage and the appropriate estimated temperature are in both cases the same. Measurement accuracy does not depend (or depends slightly) on the load current amplitude.

Repeatability of the proposed method is also satisfactory. When measurements are made with the same load currents that DUT turns-on, for the same DUT temperatures, the measured quasi-threshold voltages are always the same.

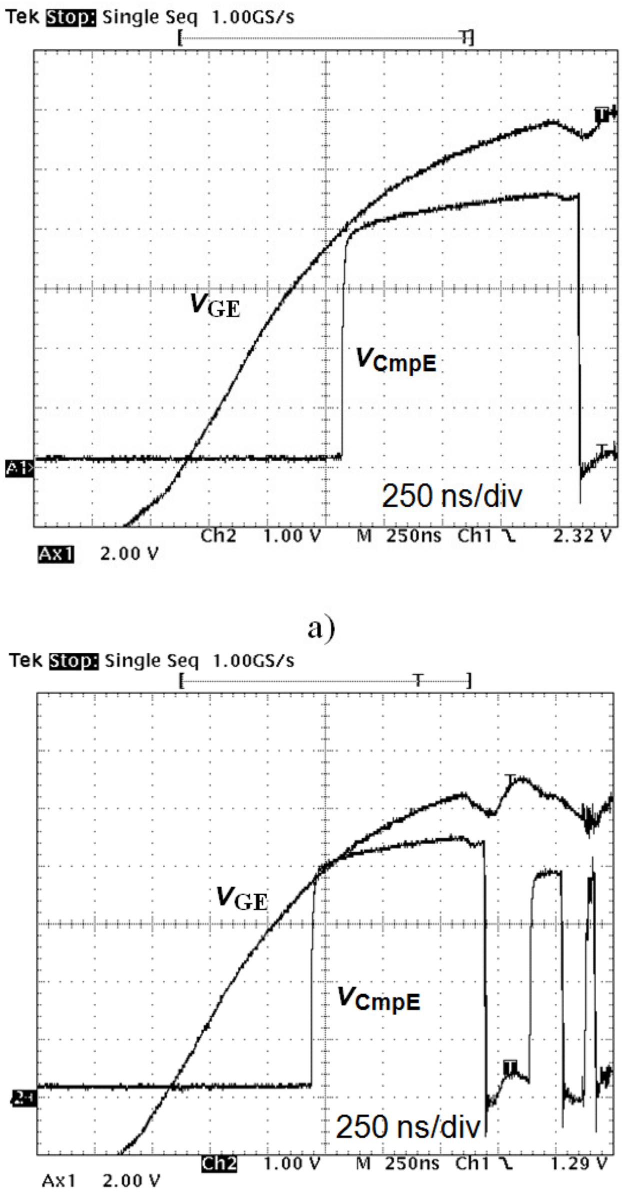
5.5 Modified gate driver circuit

For the realization of the proposed method for indirect virtual junction temperature measurement using the quasi-threshold voltage, a modified gate driver circuit has to be developed, Fig. 15. The dedicated circuit can be realized as an add-on unit for the existing gate driver circuit or as an integral part of the gate driver circuit. Due to the symmetrical construction and operation in bridge circuits, the modified driver should not be implemented on each power switch.

A modified driver has 2 comparators. Comparator $V_{L\sigma E}$ serves for capturing the moment of the quasi-threshold voltage appearance. Comparator $V_{GE} = 2\,\text{V}$ eliminates non-representative signals from the voltage $v_{L\sigma E}$. Measured voltage $v_{GE} = v_{Qth}$ is digitized and memorized. The processor used was TMS 320 F 240.

5.6 The experiment

The idea of the experiment is the following. Using a real operating power electronics circuit (a simple buck converter, Fig. 12 a) and the two-pulse loading method conduct the measurement of quasi-threshold voltages in 10 different IGBT temperature operating points. IGBT temperatures are defined and controlled by means of a temperature controlled plate, with thermocouples used as temperature sensors. The quasi-threshold voltage is measured by means of a dedicated modified gate driver circuit, Fig. 16. IGBT operating virtual junction temperature is estimated in two ways. The first temperature estimation is based on (4) using *one-point* quasi-threshold voltage calibration (at room temperature T_{j0}) and assumed temperature sensitivity coefficient $k_T = -9\,\text{mV/K}$). This is a simple method, requiring only one calibration measurement, and appropriate for a simple realization in real operating circuits. The second temperature estimation is also based on (4),



b)

Fig. 14. Waveforms v_{GE} and comparator voltage v_{CmpE} measured for the same DUT temperature, but with 2 different load current IC amplitudes; a) 250 A and b) 1000 A

but use of the two-point quasi-threshold voltage calibration (at room temperature T_{j0} and maximum temperature T_{j0MAX}) is assumed. Two-point calibration results in realistic (not assumed) temperature sensitivity coefficient $k_T = -8.75\,\text{mV/K}$. This is a more demanding method for real operation application. The experiment results are shown in Table 1.

The first row shows temperature controlled plate tem-

Table 1. Real-operation experiment results

T_j [° C] thermocouple	19.1	39.9	49.7	60	70.6	79.9	90.9	99.8	109.5	120.5
v_{GE} [V] measurement	6.909	6.736	6.648	6.571	6.489	6.403	6.306	6.215	6.126	6.021
T_j [° C] one-point estimation	19.1	38.3	48.1	56.5	65.6	75.1	85.9	96	106	117.7
T_j [° C] two-point estimation	19.1	38.9	49	57.8	67.2	77	88.1	98.5	108.6	120.6

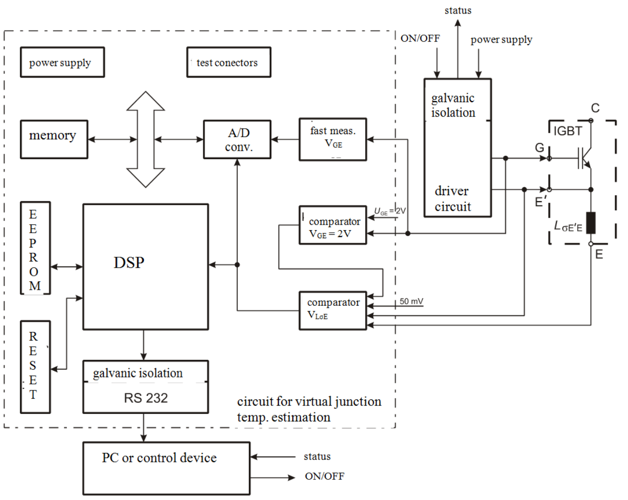


Fig. 15. Block diagram of the modified gate driver circuit for indirect virtual junction temperature measurement using quasi-threshold voltage under real operating conditions

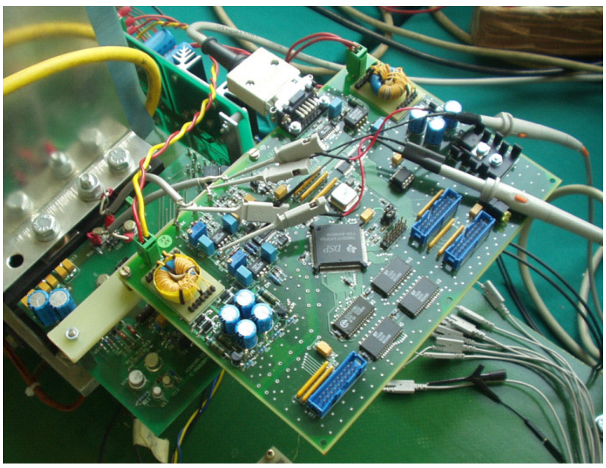


Fig. 16. Photo of the modified gate driver circuit for indirect virtual junction temperature measurement using quasi-threshold voltage under real operating conditions

peratures, measured with thermocouples, representing fixed IGBT temperature operating points. In the second row are the results of the quasi-threshold voltage measurement results using the two-pulse method and a dedicated gate driver circuit. The third row represents the results of the temperature estimation based on the measured quasi-threshold voltage and *one-point* calibration. The fourth row represents the results of the temperature estimation based on the measured quasi-threshold voltage and *two-points* calibration.

The analysis of the experiment results shows that, when temperature estimation using *one-point* calibration is used, the maximum error between the thermocouple temperature and the estimated temperature is 5 K (approx. 7%). Better results are obtained using the *two-points* calibration method, resulting in a maximum error between the thermocouple temperature and the estimated temperature of 3 K (approx. 3%). The acquired measurement accuracy is appropriate for real-operation measurements.

6 CONCLUSION

The paper proposes a new method for the estimation of power semiconductor virtual junction temperature under real operating conditions using the measurement of quasi-threshold voltage instead of the classic threshold voltage, which is extremely hard to measure under real-operating conditions.

For the method realization, a new modified IGBT gate driver circuit has to be developed, with the capability for fast gate voltage measurement. The experiment was realized using a temperature controlled plate and the two-pulse loading method, IGBT operating virtual junction temperature was estimated using the phenomenon of voltage inducing on IGBT module parasitic gate inductance during the current rise. When properly measured, this induced voltage indicates the moment of conducting channel formation, thus measured gate voltage in the moment defined by measured induced voltage is called the quasi-threshold voltage.

The experiment results show that the proposed method is accurate enough to be used for power semiconductor virtual junction temperature estimation under real-operating conditions, with a maximum relative error of 3% in the regular temperature operating region.

REFERENCES

[1] V. Blaško, R. Lukaszewski and R. Sladky, "On Line Thermal Model and Thermal Management Strategy of a Three Phase Voltage Source Inverter", in *Conference Record of IEEE Industry Applications Society*

Annual Meeting, (Phoenix, USA), pp.1423 – 1431, October 1999.

[2] A. Ammous, S. Ghedira, B. Allard, "Choosing a Thermal Model for Electrothermal Simulation of Power Semiconductor Devices," *IEEE Trans. on Power Electronics*, vol. 14, no. 2, pp.300-307, March 1999.

[3] A. Ammous, B. Allard, and H. Morel, "Transient temperature measurements and modeling of IGBTs under short circuit," *IEEE Trans. Power Electronics*, vol. 13, no. 1, pp. 12–25, January 1998.

[4] R. Krummer, T. Reimann, G. Berger, J. Petzoldt, and L. Lorenz, "On-line calculation of the chip temperature of power modules in voltage source converters using the microcontroller," in *EPE Conf. Rec.*, (Lausanne, Switzerland), September 1999.

[5] Z. Benčić, V. Šunde, Ž. Jakopović, "Estimation error of semiconductor devices virtual junction temperature in IEC's aproximate formula," *Automatika*, vol. 41, no. 3-4, pp. 153-157, 2000.

[6] Ž. Jakopović, V. Šunde, Z. Benčić, "Electro-Thermal Modelling and Simulation of a Power MOSFET," *Automatika*, vol. 42, no. 1-2, pp. 71-77, 2001.

[7] D. Barlini, M. Ciappa, A. Castellazzi, M. Mermet-Guyennet, and W. Fichtner, "New technique for the measurement of the static and of the transient junction temperature in IGBT devices under operating conditions," *Microelectronics Reliability*, vol. 46, pp. 1772–1777, 2006.

[8] D. Barlini, M. Ciappa, M. Mermet-Guyennet, and W. Fichtner, "Measurement of the transient junction temperature in MOSFET devices under operating conditions," *Microelectronics Reliability*, vol. 47, pp. 1707–1712, 2007.

[9] H. Chen, V. Pickert, D. Atkinson, and L. Pritchard, "On-line monitoring of the MOSFET device junction temperature by computation of the threshold voltage," in *PEMD Conf. Rec.*, (Dublin, Ireland), pp. 440–444, April 2006.

[10] Y.-S. Kim and S.-K. Sul, "On-line estimation of IGBT junction temperature using on-state voltage drop," in *IAS Conf. Rec.*, (St Louis, USA), pp. 853–859, October 1998.

[11] H. Kuhn, A. Mertens, "On-line Junction Temperature Measurement of IGBTs based on Temperature Sensitive Electrical Parameters," in *EPE 2009 Conf. Rec.*, (Barcelona, Spain), pp. 1-10, September 2009

[12] A. Bryant, P. Mawby, P. Tavner, "Investigation into IGBT dV/dt during Turn-Off and its Temperature Dependence," *IEEE Trans. on Power Electronics,* vol. 26, no. 10, pp. 3012-3031, October 2011.

[13] Ž. Jakopović, Z. Benčić, F. Kolonić, "Important Properties of Transient Thermal Impedance for MOS-Gated Power Semiconductors," in *ISIE 1999 Conf. Rec.*, (Bled, Slovenia), pp. 574-578, July 1999.

[14] E. Farjah et al., "Thermal Characterization of MOS-Controlled Device in Transient Conditions," *EPE Journal*, vol. 4, no. 2, pp. 33-37, June 1994.

[15] Blackburn D. L., "A Review of Thermal Characterisation of Power Transistors," in *SEMITHERM 1988 Conf. Rec.*, (San Diego, USA), pp. 1-7, February 1988.

[16] Sze S.M., *Physics of semiconductor devices*, New York: J. Wiley & Sons, 1981.

[17] A. Castellazzi et al., "A study of the threshold-voltage suitability as an application-related reliability indicator for planar-gate non-punch-through IGBTs," *Microelectronics Reliability*, vol. 47, pp. 1713–1718, 2007.

[18] Ž. Jakopović, V. Šunde, Z. Benčić, "From Transient Thermal Impedance Measurement to Successful Electrothermal Simulation," in *EPE-PEMC 2002 CD Conf. Rec.*, (Dubrovnik, Croatia), pp. 1–13, September 2002.

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