Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 1617 – 1620

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

A PTAT-based heat-flux sensor for the measurement of power losses through a calorimetric apparatus

Demetrio Iero[a],*, Francesco G. Della Corte[a], Massimo Merenda[a], Corrado Felini[a]

[a] *University "Mediterranea" of Reggio Calabria, Via Graziella Feo di Vito, 89122 Reggio Calabria, Italy*

Abstract

A calorimetric apparatus for the measurement of the power losses in switching devices, *e.g.* MOSFETS, is presented. The technique uses an heat-flux sensor made of two, new and custom designed, proportional to absolute temperature (PTAT) CMOS sensors, and allows to achieve accurate results without the use of costly measurement equipment. The calorimetric apparatus allows the measurement of the power dissipated by devices operating in repetitive dynamic conditions, without the problems associated with electrical measurements. Coupled to a control/readout circuit and a thermoelectric module (TEM), it allows the determination of the power dissipated by a semiconductor device, regardless of its switching frequency.

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference

Keywords: Calorimetry; Heat-flux sensor; Powe losses measurement; PTAT sensor;

---

1. Introduction

The measurement of the power dissipated by a semiconductor device is crucial to evaluate the performance and reliability of a power electronics systems. The electrical measurement methods can be performed easily and with good precision for DC and low frequency waveforms. However, with the increase of the converters efficiency and the semiconductors operating frequencies, efficiency measurements become increasingly difficult due to errors associated with the calculation method of the power losses as the subtraction of the input and output power, and due

---

* Corresponding author. Tel.: +39-0965-1693441.
E-mail address: Demetrio.iero@unirc.it

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.474

to the limited precision of the digital measurement instruments, that are also affected by phase shifts between acquisition channels, probes delays, sampling errors, and non-linearities of A/D converter [1].

The calorimetric method allows to measure the heat dissipated by a device and therefore its power losses, and is not affected by the aforementioned problems also for very fast signals.

Several calorimetric schemes have been presented in literature [1,2]. In their simplest form, they are based on a heat-flux sensor, in which the flowing heat generates a temperature gradient proportional to the heat-flux. Our set-up is very simple because it does not require the use of a closed chamber or sophisticated controls.

The presented heat-flux sensor was realized by stacking two newly designed microchips [3], each integrating a temperature sensor and control electronics. The working principle of the apparatus was presented in [4]. It uses a Peltier heat pump to absorb the heat generated by the DUT and maintain its package at ambient temperature, thus minimizing the heat leakage toward ambient and improving the accuracy.

2. PTAT Sensor

The heat-flux sensor of the apparatus uses two integrated microchips, each including a PTAT sensor in CMOS technology, that perfectly fit low cost, high performance, and low power consumption.

Assuming for PNP BJTs the collector current given by $I_C = I_S\, e^{((qV_{EB})/\eta kT)}$, with I_s the saturation current of the emitter-base junction, V_{EB} the emitter-base voltage, k the Boltzmann constant, q the electronic charge and η the ideality factor, if two identical transistors ($I_{S1} = I_{S2} = I_S$) are biased at collector currents of I_{ref} and I_o respectively, the difference between the emitter-base voltages of the two BJTs has a linear dependence on T, according to the equation $\Delta V_{EB} = V_{EB1} - V_{EB2} = V_t \ln(I_{ref}/I_s) - V_t \ln(I_o/I_s) = kT/q \ln(I_{ref}/I_o)$, where $\eta=1$ was assumed.

The PTAT exploited in our work was designed to provide a high sensitivity in the temperature range from room temperature to 100°C. The temperature sensor consists of a PTAT voltage generator and a differential amplifier, as depicted in Fig. 1a.

To obtain a proportional output signal with respect to absolute temperature, two diode-connected BJTs, driven by different currents, were realized. The two PNP transistors Q1 and Q2 are identical and work in active region. However, due to the different aspect ratios W/L of M1 and M2, if the channel length modulation can be neglected [5], Q2 is driven by a current I_o that is $n \times I_{ref}$, where n is the channel width ratio W_{M1}/W_{M2}.

The reference current I_{ref} is generated through an integrated bias current generator (BBIAS) that delivers a constant current of 11.5 μA. The source is designed to supply each diode-connected BJT with currents that are independent from V_{dd}.

In Fig. 1b the signal output of the integrated PTAT is showed. It presents a good linearity (R^2=0.99962) in the temperature range of interest (20°C-90°C) with a sensitivity of 19.1 mV/°C, measured at the amplifier output.

In the same Figure, the simulated characteristic is provided for comparison. The amplifier stage was designed to get signal levels that could be reasonably applied to an ADC, while preserving linearity.

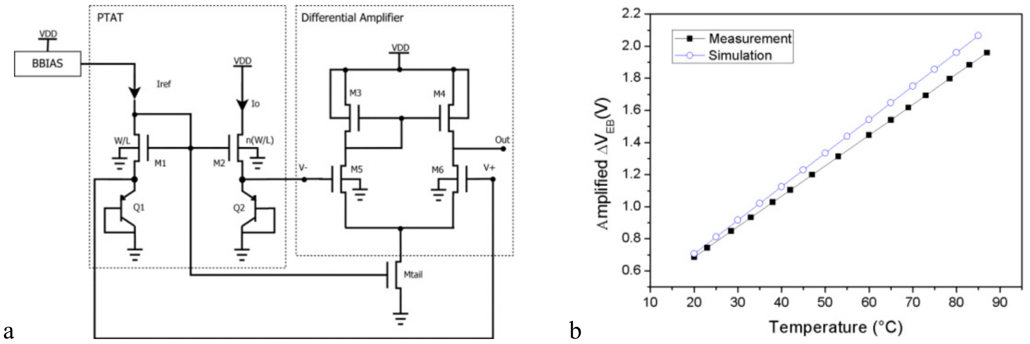

Fig. 1. (a) architecture of the integrated PTAT with differential amplifier; (b) experimental and simulated characteristic of the PTAT sensor.

3. Apparatus

The apparatus is based on a heat-flux sensor, a thermoelectric module (TEM), and a readout-control circuit. The TEM absorbs the heat generated by the DUT and maintains the device at ambient temperature, allowing to minimize the heat exchange with the surrounding air. The sensor is positioned between the DUT and the TEM and, as there is virtually no heat exchange with the air, it allows to detect all the heat generated by the DUT.

DUT, sensor and TEM are isolated from the ambient with a polystyrene structure. An heat-sink with active cooling is attached to the thermoelectric module to dissipate the heat. Finally, heat spreaders are used to distribute uniformly the heat on the sensor surfaces. The structure of the apparatus is shown in Fig. 2a, and a picture of the whole system is provided in Fig. 2b.

Differently from previous realisations [4,6,7], in this work a highly precise heat-flux sensor is obtained by stacking two custom designed PTAT sensors presented in the Section 2. These sensors offer high accuracy and high linearity, as shown in the output voltage vs. temperature curves in Fig. 1b.

A control board includes a microcontroller that reads the temperatures of the sensors in the apparatus and implements a digital PID (proportional–integral–derivative) regulator that control, through a PWM signal, the bias of the TEM, regulating the quantity of absorbed heat and the temperature of the DUT. This allows to keep the average device temperature comparable to that of ambient, minimizing the heat transfer by convection. An expressly made PC application monitors the measurements and allows to customize the working parameters of the controller. The board also includes circuitries for the conditioning of the analog signals, and a 24-bit A-D converter to acquire the voltage from the PTAT sensors. PT100 RTDs are used to monitor the temperature of the DUT surface, and the ambient temperature. An external board convert the PWM control signal generated by the microcontroller, to a voltage value for the TEM biasing.

The control regulates the PWM output such that the temperature of the device converges to that of the ambient. When the DUT is in thermal equilibrium and the heat leakage minimized, it is possible to acquire the temperature gradient (ΔT) across the heat-flux sensor that will be representative of the power dissipated by the device.

The losses are determined in two steps. A calibration procedure is necessary to determine the relation between the measured ΔT and the power dissipated by the DUT in DC operation, when it is possible to measure the losses with higher precision. After the calibration, the power losses can be calculated at any operating conditions by acquiring the corresponding ΔT and comparing the value with the calibration curve to obtain the estimated power loss in that particular condition.

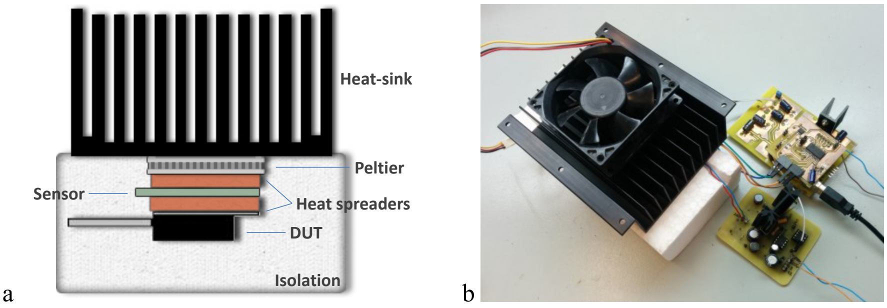

Fig. 2. (a) structure of the apparatus: the sensor is between the DUT and the TEM and isolated from the ambient with polystyrene layers; (b) image of the apparatus and control system, with the control, acquisition and regulation boards.

4. Measurement and results

Fig. 3a shows a calibration curve that relates the power dissipated by a MOSFET and the temperature difference measured by the sensors; the figure shows a good linear relation between the ΔT and the power dissipated. The calibration is performed with the device operating in DC and the power is calculated as $V_{DS} \times I_D$, measured with two HP 34401A digital multimeters.

After the calibration, the power dissipated by the DUT in switching operation was characterized with our apparatus and the results were compared with the power measurement made with a LeCroy Wavepro 434 oscilloscope. The MOSFET gate was driven by a square wave at various frequencies, and different loads connected on the drain. Fig. 3b shows the power losses, estimated by our system through interpolation by mean of the previous determined calibration data and compared with the oscilloscope measures, at various switching frequencies.

At higher frequencies and higher values of power losses, the difference between measurements made with the two different set-ups increases, due to the underestimation of the losses measured through the oscilloscope with highly distorted signals.

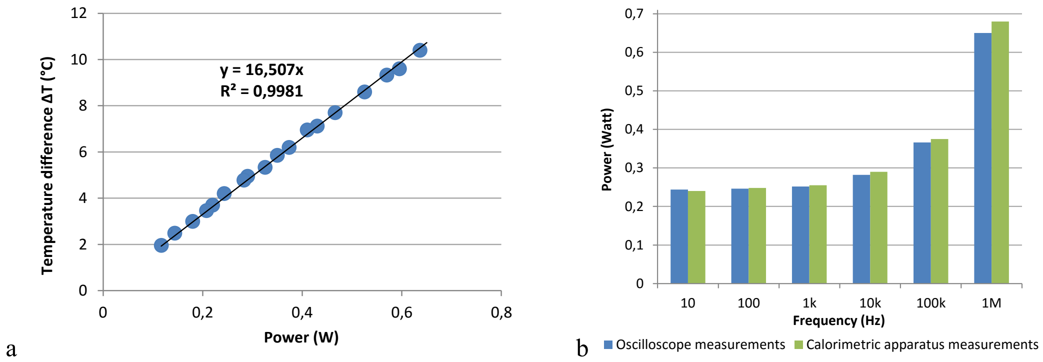

Fig. 3. (a) calibration curve of the apparatus: temperature difference (ΔT) vs power dissipated by the DUT in DC operation; (b) comparison between the losses estimated by our system and those measured by a digital oscilloscope at different frequencies.

5. Conclusions

A calorimetric apparatus that consists a of heat-flux sensor made with PTAT sensors, a thermoelectric module and a control circuit, has been realized and used to measure the switching and conduction losses of devices operating in dynamic repetitive conditions.

The TEM is used to absorb the heat and to keep the device in thermal equilibrium with its surrounding, minimizing the heat leakage. The ΔT measured across the heat-flux sensor is proportional to the power dissipated by the device. This set-up is simpler than other calorimetric methods and can be built with a small expense.

After an initial calibration step, the power losses of a DUT can be estimated on the basis of the calibration data for any arbitrary operating condition, even with electrical signals at high frequency for which the power losses measured with traditional instruments can present large acquisition errors.

References

[1] C. Xiao, G. Chen, W. Odendaal, Overview of power loss measurement techniques in power electronics systems, IEEE Trans. Ind. Appl. 43 (2007) 657–664.

[2] D. Christen, U. Badstuebner, J. Biela, J.W. Kolar, Calorimetric power loss measurement for highly efficient converters, in: The 2010 International Power Electronics Conference, 2010: pp. 1438–1445.

[3] C. Felini, M. Merenda, F.G. Della Corte, Design and implementation of high resolution, high linearity temperature sensor in CMOS process, in: 2015 XVIII AISEM Annual Conference, IEEE, 2015: pp. 1–4.

[4] D. Iero, F.G. Della Corte, G. Fiorentino, P.M. Sarro, B. Morana, Heat flux-based sensor for the measurement of the power dissipated by switching devices, in: AMPS 2013, Aachen, Germany, 2013: pp. 19–23.

[5] B. Razavi, Design of Analog CMOS Integrated Circuits, (2001).

[6] D. Iero, F.G. Della Corte, G. Fiorentino, P.M. Sarro, B. Morana, Heat flux sensor for power loss measurements of switching devices, in: THERMINIC 2013, IEEE, Berlin, Germany, 2013: pp. 327–330.

[7] D. Iero, F.G. Della Corte, G. Fiorentino, P.M. Sarro, A calorimetry-based measurement apparatus for switching losses in high power electronic devices, in: IEEE International Energy Conference ENERGYCON 2016, Leuven, Belgium, 2016, pp-1-5.