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Embedded set of sensors for power electronic modules

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Abstract

This study deals with the challenges for driving Wide Band Gap modules to maturity. In this study, development, integration and signal processing techniques of several types of sensors are studied. Industrial and academic partners, within CAPTIF project, are proposing complementary skills and experiences in the technological and scientific domains: multi-physic sensors, signal processing, integration and reliability for power electronics. Nanoparticle-based strain gauges, temperature sensors and electromagnetic array sensors will be validated and integrated in power an electronic power module. A specific multi-physic model will be developed in order to specify the best location of interest within the power module. These features will result in a better knowledge of real-time current density location, as well as current frequencies. For both sensor types, the data packaging will be challenging spin-offs. Finally, advanced data processing techniques – estimation as well as signal processing – will be adapted to numerous sensor outputs. A clean room process flowchart will be established to guarantee an advanced pre-industrial prototyping.

Introduction

The joint emergence of Wide Band Gap materials (SiC, GaN, C) and new generation hybrid integration techniques significantly enhance performances of power electronic modules. Such modules should operate in severe environment and constraints: high temperature high power density, fast switching, etc. The challenges for driving these new modules are about developing, integration and signal processing techniques of several types of sensors. Industrial and academic partners, within CAPTIF project, are proposing complementary skills and experiences in the technological and scientific domains. Indeed, multi-physic sensors, signal processing, integration and reliability for power electronics are the main themes studied.

The dedicated multi-physic model highlights the best location for inside measurement. The sensors to be integrated fulfil high integrability and efficiency. To do so, nanoparticle-based strain gauges, temperature sensors and electromagnetic array sensors will be validated and integrated. The main interest of such sensors is their low power consumption, their miniaturization and their possible integration as well as their accuracy. Electromagnetic sensors will be issued from previous studies and adapted to this dedicated device. For both sensor types, the data packaging will be challenging spin-offs. Finally, advanced data processing techniques – estimation as well as signal processing – will be adapted to numerous sensor outputs. Moreover, a clean room process flowchart will be established to guarantee an advanced pre-industrial prototyping. The industrial partners will certify how far the project outputs will be suitable for advanced health monitoring of power device. Finally, these features will result in a better knowledge of electro thermomechanical behaviour of power modules. Combined with the state of health indicator, the measurements or observations will be applicable to power modules health management and robustness.

This paper presents the results obtained in each scientific and technical objectives. The first part of the paper is devoted to describing overall specifications. The second section highlights the design of a set of sensors and their first characterization results. In the third part, multi-physics modelling and preliminary reliability tests will be presented and analysed. The fourth part is dedicated to preliminary developments completed on data processing techniques, as far as filtering and variable estimation are concerned.

Program structure

Five partners carry this project: 2 research laboratories and 3 companies. Research laboratories will design electromagnetic sensors, define the data processing techniques and the multi-physics modelling as well as perform reliability tests for both sensors and functionalized power devices. Industrial partners will provide nanotechnology sensors, adapt the clean room process and guarantee the technology readiness level.

As illustrated in Figure 1, six work packages are defined. They are linked with the main role of each partner. The main deliverables are thesis reports, technical reports as well as new products. Effectively for both industrial partners, their product will be updated following the

CAPTIF results. Indeed, Nanolike sensors should be applicable to new markets, and more precisely to the power electronics components and systems. aPsi3D products will be fully characterized by the use of several sensors and it is imagined that some future power modules will integrate some sensors.

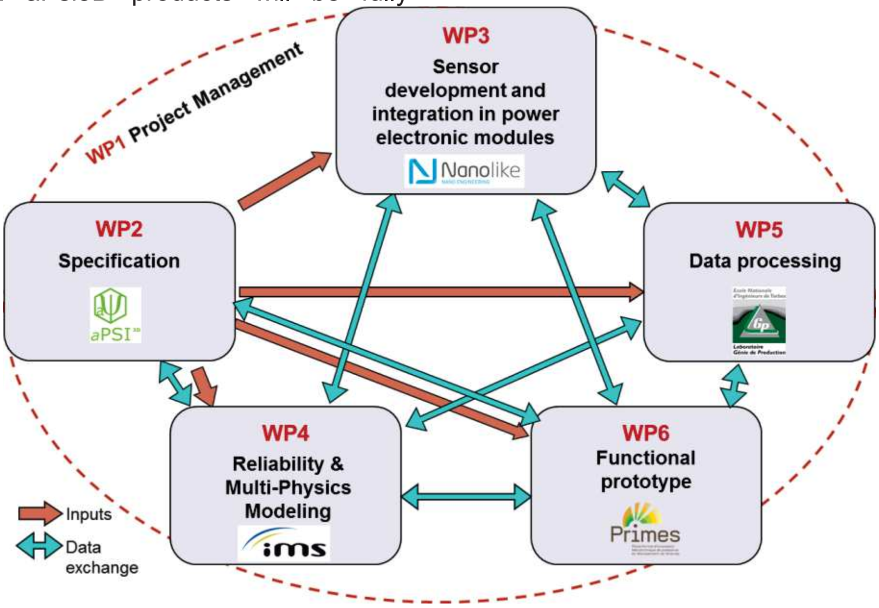

Figure 1: Work Package overview

Specification

The product target for the integrated sensors is defined as a sandwich type power module as illustrated in Figure 2.

Based on the geometry and the power density, the specification defines the process related constraints. Indeed, the maximal temperature occurring during the process, and the different process stage are specified. They are a part of the sensor process integration constraint.

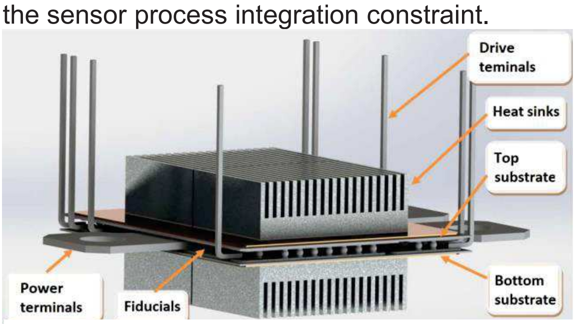

Figure 2: agile Power Switch 3D-Integration power module

Sensor development

To achieve these specifications, three types of sensors are developed: nanoparticle-based strain gauges, temperature sensors and electromagnetic field sensors.

Electromagnetic Field Measurement Principles

With the increase of the operating frequencies, switching rates and voltage/current levels in actual electronics systems, high electromagnetic noise and activity are now emerging over a wide frequency band [1]. These can be considered as a good way to acquire an image of real conductive behavior of the devices, with a critical drawback for the integrity of the system: EM couplings and Electromagnetic Compatibility (EMC) increase problems in microelectronics [2]. Near-field measurement techniques have attracted a great deal of attention because of their high temporal and spatial resolutions [3].

The design of EM sensors is focused on magnetic near field measurement. The steps defined for the design of antennas deals with the characterization and the integration and validation. The antenna fulfills the following requirements: to be a punctual receiver; to not disturb the magnetic field distribution $\vec{H}$; to be sensitive only to the magnetic field. The final design is a $3\,mm$ radius loop associated with $4\,cm$ adapted transmission line. Moreover a parametrized study establishes the size and geometry of loop as well as the influence of the transmission line, for a given radius, length and substrate constitution. Finally as illustrated in Figure 3 the $\vec{H}$ field antenna is characterized and modeled as a R, L C equivalent electrical scheme. The simulation results is compared to the impedance measurement $|Z|$.

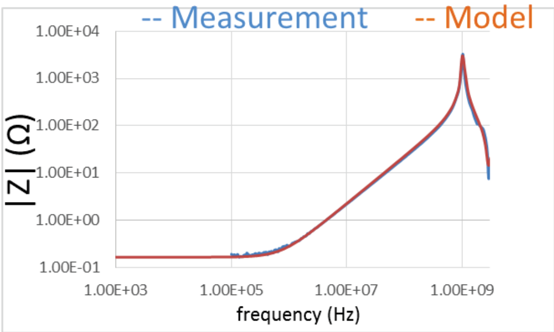

Figure 3: Impedance characterization of the antenna

Nanoparticle sensors

Today strain measurements are mainly made with two technologies: metallic strain gauges and semiconductor strain gauges. Metallic strain gauges have a small sensitivity (gauge factor = 2) but have a significant strain range (typically ± 3%). On the contrary semiconductor strain gauges have a higher sensitivity (gauge factor ~ 100) but a smaller strain range (typically ±0.5%). Nanoparticle-based strain gauges developed by Nanolike look like classical resistive sensors, except that the active area is made of a compact assembly of gold nanoparticles as illustrated in Figure 4.

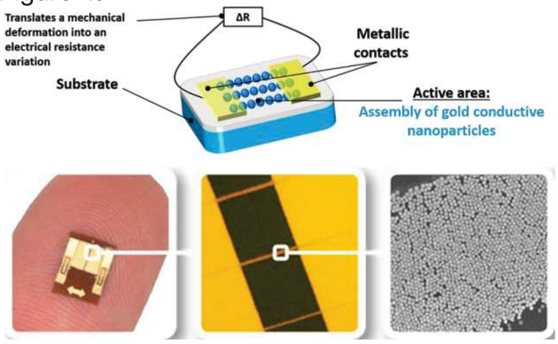

Figure 4: Nanolike - nanoparticle sensors

As a consequence they combine a high sensitivity (gauge factor ~ 20), because of the tunnel mechanisms governing their electrical properties [4] with a small electrical consumption which makes them very good candidates to be deployed as non-invasive sensors which is one objective of the project.

Today, three main technologies are generally used to measure temperature: thermocouples, thermistors and resistance temperature detectors. Thermistors and Resistance Temperature Detectors (RTD) exhibit correct performance but their electrical consumption and the difficulty of their integration on specific locations do not push them as good candidates to be spread onto PCBs. Thermocouples are easier to integrate on specific locations but one junction needs to be placed at a temperature reference, which leads to problems when the monitored devices are not in a controlled environment. Furthermore, sensitivity and accuracy of common thermocouples is relatively low.

Because of these limitations, nanoparticle-based temperature sensors can be better candidates to be directly integrated on devices to monitor their temperature. As nanoparticle-based strain gauges, they are made of a compact assembly of gold nanoparticles the resistance of which depends on temperature. First experiments made on rigid silicon substrates indicate that these sensors can measure temperature with a good sensitivity (-0.5%/°C) and a very small electrical consumption (smaller than 1μW). Moreover, as the active area is very small (typ. 0.1mm²), they can easily be placed in confined areas.

Multi-Physics Modeling

A multi-physics model is necessary to correlate the data obtained by the sensors with the simulated ageing indicators. Multi-physics modeling allows catching in a more precise way the combined influence of several physical phenomena at stake rather than separately (mechanical, thermal and electrical phenomena). Multi-physics coupling and modeling tools, based on finite elements approach, will be used to provide complete numerical model of power modules on which sensors are integrated. The multi-physics models will be further validated thanks to the test vehicle reliability testing results.

The multi-physics modelling of the complete module allows identifying the sensitive or fragile areas of the module to be monitored by the sensors. It allows making the link between accelerated ageing tests and real operation thanks to an indicator of the ageing state of the power module. Indeed, the health state indicator defined is the stored energy density function which corresponds to the strain energy density – SED of a material related to its deformation gradient:

$$SED = \int_{\varepsilon_1}^{\varepsilon_2} \sigma d\varepsilon \qquad 1$$

Where ε_1 and ε_2 are the strain values of the material considered after a complete thermal cycle. To monitor the increase of the SED, a finite element simulation is used. A thermal cycle $T \in [-55°C; +165°C]$ is applied to a simplified power assembly composed of power device, a substrate and. The SED is monitored within the sintering material, all along the thermal cycle and increase step by step, as illustrated in Figure 5.

Such results aim at supplying tools and methodologies to help the design and the sensor integration in power modules.

It would be desirable that the real data provided by the sensors allow estimating in the same way the state of ageing of the module.

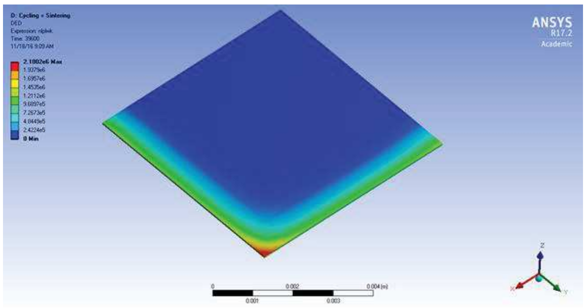

Figure 5: Strain Energy Density computed.

Data processing

The purpose of this study is to propose adapted methodologies and designed algorithms of data processing for the monitoring of a power electronics device. Then, efficient, feasible, fast response time and adaptable supervision technique will be selected with respect to the different monitored variables.

The electro-thermal behavior of a plane surface made of several plane components and heterogeneous materials is simulated. For our purpose, this simulation is performed by spatial discretization, where elementary surfaces are defined. Each surface is modeled as an equivalent electrical circuit. T is the temperature, t the time, k and α some coefficients related to the geometry and materials, and S the power source. To do so, the thermal law:

$$\frac{\partial T}{\partial t} = k\nabla^2 T + \alpha S \quad (2)$$

is expressed in a state space formulation as detailed in [5]:

$$C_{th}\dot{T} = AT + Bu \quad (3)$$

Where T is a vector of local temperatures, C_{th} is a diagonal matrix of thermal capacities, A the thermal resistances matrix, B is the command matrix and u is the vector of boundary conditions made of temperature and heat sources.

That model will be combined to local temperature measurements with nanoparticle sensors. Finally, the aim of the study is to estimate the temperature at any point O of a power electronic module. Nevertheless, this simple approach has some drawbacks. One of them is the size of the observer state space model. To overcome this, the study explores two mains alternative strategies: to reduce the model order; to identify a simple transfer function. This last strategy deals with the idea to model the relationship between two local temperature values by an identified transfer function as the Strejc model or Hudzovic model.

Indeed, as depicted in Figure 6, the objective is to estimate the temperature value at a given point O. O is situated on the top surface of power module which can be modelled as a discretized surface, as in Eq(3). This value can be obtained thanks the two previously mentioned strategy. F_1, F_2, F_3, F_4 and F_5 model the transfer function between points.

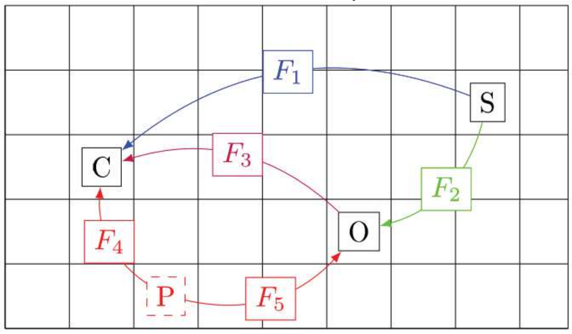

Figure 6: Observer principle

C is where the sensor is set. S is the power source. P is a heat or power disturbance. The value of O should be obtained using a reduced observer, or with a simpler transfer.

Conclusions

CAPTIF aims at reaching a high monitoring knowledge of electro-thermo-mechanical behaviour of power electronics devices. This will be possible thanks to a set of integrated sensors associated with advanced data processing techniques. Indeed optimal design of power electronics would become more accurate than previously, as well as a better knowledge of reliability aspects would be reached.

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