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Improving ICs reliability with high speed thermal mapping

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ABSTRACT

The power elements are the weak parts of integrated circuits (ICs), in fact, through these elements the power is usually dissipated as heat with unavoidable thermal and mechanical stress. On the contrary the logic parts of ICs stay at lower temperatures. This gives rise to two effects: the non-uniform generation of the heat across the die and the temperature gradients. Understanding these phenomena is very important to choose the right location of sensitive components, like thermal sensors, in order to improve reliability. As a consequence, the knowledge of the temporal evolution of the temperature distribution plays a very important role to improve both design and lifetime. Here we show how a single IR sensor based experimental setup is suitable to catch very fast thermal events performing high spatial resolution. We demonstrate the effectiveness of the method maps for three IC samples where an accurate thermal modeling for reliability has been obtained and validated, greatly improving the overall quality.

1. Introduction

The self-heating of an integrated circuit plays a key role in reducing its lifetime mostly when the power devices work in linear mode operation. Usually, the power element of the circuit covers a large portion of the active area, whereas the parts managing signals have a negligible power dissipation. This leads to a non-uniform distribution of the temperature and to the presence of relevant thermal gradients across the device. In a very short time some parts of the surface, i.e. the power sections, undergo high temperature variations due to high current density whereas the logic control sections are not affected by high currents and their temperature is almost constant. The uneven temperature distribution can produce many problems in the device operations, negatively affecting the reliability [1,2]. The phenomenon is more evident when the power dissipation is occurring in a very short time, because in this case the temperature variation takes place in a time not long enough to allow a uniform heating of the whole structure. Many smart power devices could include advanced protective functions based on integrated temperature sensors. In order to achieve a proper design and an accurate component placement in the layout, it is very important to know the value of the temperature gradient and its spatial localization. There are different methods to evaluate the temperature of the die. These methods are based on computer simulations [3–5] or on direct measurements while the devices are operating [6–9]. This latter approach is a real challenge. The main difficulties are related to the required performances of the acquisition system in terms of sample time and to the measurement process that is often invasive. Indeed, in order to perform the measurement, the devices under test (DUT) must be opened to realize a window for the infrared electromagnetic radiation, thus modifying their real structure. When the heating is a very rapid process and the areas to be analyzed are very small, high performances in terms of spatial and temporal resolution are required. At the best of our knowledge the commercially available instruments, such as thermal cameras, do not meet these requirements. In this paper, we describe some of real issues experienced in power electronics devices due to a slightly flawed design, which sometimes results in an unpredictable thermal distribution. We highlight how the short-circuit protection may be ineffective if a late detection of the overheating occurs due to the wrong location of the thermal sensors. Moreover, we show how, in a buck switching regulator, an uneven thermal distribution takes place during the working operations when the devices design is not properly optimized. We demonstrate that the thermal information obtained by a suitable temperature mapping system are enough to solve the above described problems, greatly improving the design and the reliability and how sometimes it is possible to perform this kind of study in a completely non-invasive way with a better reproduction of the effective operative conditions.

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2. Thermal gradients in ICs

Thermal gradient can affect many electrical parameters, especially in case of high power dissipation. In the case of linear voltage regulator, we can mention: output voltage (V_{out}) regulation, over-current (OCP) and over-temperature protection (OTP) limit. The shift of the first parameter can be seen just as incompliance with the device datasheet whereas the shift of latter two can lead to severe consequences. Thermal gradient can cause the increase of the OCP current limit leading to a positive feedback loop between the power dissipation and the thermal gradient. In the majority of cases this ends with the devices failure, and sometimes with an “explosion”. The chip can be saved by the OTP circuit, but just in the case of precise temperature monitoring of the hottest point. However, this possibility can be also affected by the thermal gradient because if the temperature sensor is placed out of the power device area (e.g. in the perimeter), probably it will sense lower temperatures and it will not protect the device against the failure. As a result, it is mandatory that the temperature and current sensors of the mentioned OTP and OCP can be correctly placed at the point where the hot-spot is expected for a proper overheating control design. Taking into account that the reduction of the dimensions of the integrated devices and of the packages is continuously increasing, the localization of real-hot spot with very high spatial resolution plays a key role in order to improve the control circuit design aiming to prevent overheating.

3. Non invasive temperature measurement

Detecting small temperature differences on surfaces whose extension is sometimes less than one mm^2 is a challenge. In addition, in case of overloads, the transients last for some hundreds or tens of microseconds. Hence a conventional high-resolution thermal camera, whose frame rate is usually in the millisecond scale, cannot detect these thermal events. Therefore, we developed a setup to capture very high speed thermal transients [6]. It is based on the scanning technique thus acquiring the signal coming from each micrometric area (i.e. a pixel) at very high speed. The instrument is equipped with a XY mechanical scanner, a broadband reflective microscope objective and a high-speed optical detector optimized for the far infrared (see Fig. 1). The objective focuses the thermal radiation emitted from the surface onto the optical detector that evaluates, point by point, the temperature of the DUT.

To collect the infrared radiations emitted by the DUT, a partial removal of the covering package over the die is often needed, except for those small devices characterized by a thin layer of package coverage. In those cases the opening process is not required, indeed, if the packaging layer is small enough, the temperature distribution on the external well represents the thermal behavior of the active parts underneath the insulating layer, thus allowing the reconstruction of the temperature on the covered chips.

For each single pixel scanned on the surface the instrument performs an acquisition that is synchronized with a current pulse supplied to the DUT, capturing a temporal array with a time resolution of 5 µs (i.e. acquiring at 200 kS/s). The synchronization between the current pulse and the acquisition is accomplished by triggering the sampling process with the same signal that activates the DUT. It is also possible to insert a tunable delay between the “enable” signal and the start of the acquisitions. Obviously, in order to spatially reconstruct the complete thermal evolution taking into account all the captured temporal arrays, the DUT undergoes a stressing event for each current pulse, i.e. for each pixel of the thermal map. For this reason, the time interval between two pulses has to be long enough to assure that the starting temperature is the same for each current pulse. This interval is experimentally defined through preliminary tests executed on the DUT, indeed it strongly depends on peculiar structure of the DUT and on the expected dissipated power during the current pulse. If the starting temperature and the thermal stress are the same for each acquired pixel, the thermal maps will correctly describe the temperature behavior due to the current pulses. A 36× lateral magnification objective has been used to collect the electromagnetic field emitted by the DUT and to focus on the 1 mm^2 active area of the detector. The optical assembly allows a resolution of about 27 µm × 27 µm squared area. The scanned grid can be suitably adjusted and adapted to the area of interest on the device surface.

Analyzing the sequence of thermal maps, it is possible to localize the hot-spots and to acquire valuable information to improve the design of the protection control system, with a special attention to the correct position of the temperature sensors. Moreover, it is possible to reconstruct a thermal map that is not associated to a single instant of the acquired thermal event but rather on the whole acquired time-evolution. This remarkable thermal map will be obtained by plotting the maximum values of temperature for each temporal array acquired on the surface. Hence, this map describes the maximum temperature for each point on the surface and it localizes the hot spot during the entire working cycle.

4. ICs reliability improvement

The explained technique has been applied on three different analog IC products, i.e. two LDO (Low Dropout Voltage) regulators with different output current and on a High Current Synchronous Buck Regulator.

4.1. Results on LDK220 voltage regulator

In STMicroelectronics a new LDO regulator has been recently developed (LDK220). It works with maximum input voltage 18 V and it is able to drive currents up to 200 mA. The device is protected with both OCP and OTP. The over-current protection is set to 400 mA.

Fig. 2 shows the opened package i.e. without the top shield of the structure, realized for the thermal analyses.

The performed electrical tests pointed out that the DUT does not survive the short circuit tests at higher input voltage (greater than 14 V) (see Fig. 3). The failure is mainly due to the improper operation of the OTP circuits influenced by temperature gradients. In particular, the problem was caused by the position of a temperature sensor in the chip

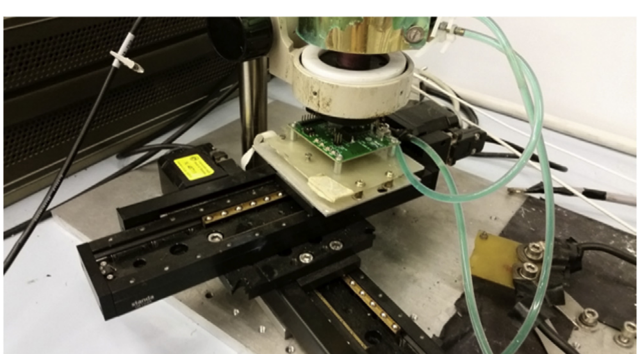

Fig. 1. Measurement instrument.

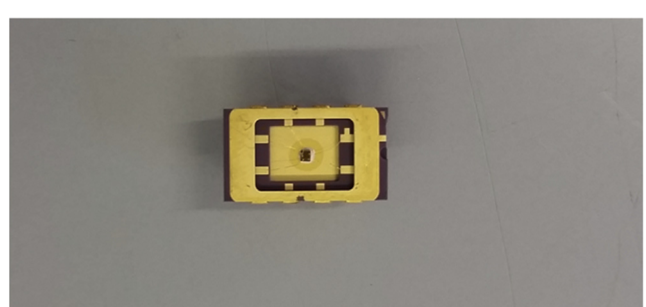

Fig. 2. LDK 220 regulator.