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Towards prognostics and health monitoring: The potential of fault detection by piezoresistive silicon stress sensor

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ABSTRACT

A piezoresistive silicon based stress sensor has been demonstrated successfully as an effective tool to monitor the stresses inside electronic packages during various production processes. More recently, the sensor has been evaluated as a sensor for Prognostics and Health Monitoring (PHM) systems. This paper presents a systematic approach that evaluates its performance from the perspective of failure mode detection. A detailed Finite Element method (FEM) model of existing test vehicles is created. The test vehicle consists of six DPAK (Discrete Package) power packages and three stress sensors. The results of simulation are verified by the signals obtained from the stress sensor as well as the supplementary warpage measurements. After inserting various failure modes into the model, statistical pattern recognition algorithms are implemented for fault detection and classification. The proposed technique can identify detectable failures during reliability testing by utilizing the database of stress sensor responses for healthy and unhealthy state. Thus, the results establish a baseline for the applicability of the piezoresistive stress sensor for an on-line monitoring PHM methodology.

1. Introduction

The piezoresistive silicon based stress sensor offers unique advantages, including direct measurement of the mechanical stresses and easy integration with existing systems. The sensor has demonstrated its capability of monitoring the stresses during the transfer molding process [1]. In Refs [2,3]., the evolution of the stresses in a package during the post mold curing process was investigated by the sensor. The underfill process was also studied by the sensor in Refs. [4,5]. The sensor was applied further to monitor the stresses during reliability testing. In Ref. [6], Roberts et al. studied the evolution of stresses during thermal cycling reliability tests. Similar results were presented by Shindler-Saefkow et al. [7] and Yu-Yao Chang et al. [8].

More recently, the sensor has been investigated for Prognostics and Health Monitoring (PHM) systems [9–12]. PHM has emerged as a promising solution to the need for more accurate life time prediction of new products that are more complex but have reduced development time. PHM combines in-situ measurements, data acquisition and interpretation of measured parameters, based on which the state of health of the electronic system can be assessed [13].

In this paper, the piezoresistive silicon based stress sensor is studied for a data driven approach to PHM. It has been shown that delamination can be detected by sensing the signal change of the sensor [14]. However, a systematic study about how different failures can influence the sensor output is missing. FEM analysis is conducted to fill this gap. First, various failure modes are introduced into a predictive model and the response of the sensor is investigated.

Collected data is then used to study the applicability of statistical pattern recognition algorithms. Three different algorithms are studied: Mahalanobis Distance (MD) [15] and Singular Value Decomposition (SVD) [16,17] for damage detection and Support Vector Machines (SVM) for damage typology [18]. The applicability of these algorithms to the current problem is discussed.

2. Stress sensor

This study focuses on an application of piezoresistive silicon-based stress sensor, called IForce. In this section the general working principle and construction of the sensor are presented.

The sensing elements are created by the channels of MOSFET transistors that are oriented in such a way that the change in stress is changing their resistivity. By measuring the currents flowing through the sensor in-plane shear stress, σ_{xy}, and difference in in-plane normal stress components, $\sigma_{xx} - \sigma_{yy}$, can be calculated from the following relations:

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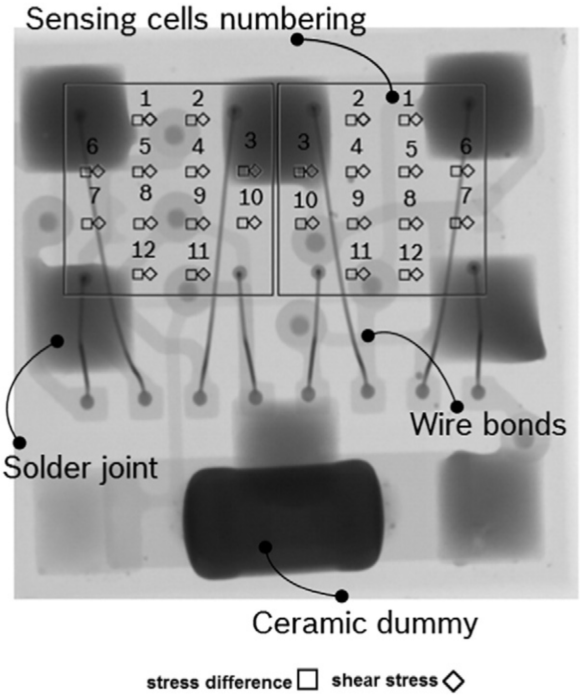

Fig. 1. X-Ray image of stress sensor used in this study.

$$\sigma_{xy} = \frac{1}{\pi_{11}^{n} - \pi_{12}^{n}} \frac{I_{OUT} - I_{IN}}{I_{OUT} + I_{IN}} \tag{1}$$

$$\sigma_{xx} - \sigma_{yy} = \frac{1}{\pi_{44}^{p}} \frac{I_{OUT} - I_{IN}}{I_{OUT} + I_{IN}} \tag{2}$$

where:

π_{11}, π_{12}, π_{44} – piezoresistive coefficients of silicon

I_{IN}, I_{OUT} – currents measured at the input and output of the sensor, respectively.

The use of MOSFET technology enables the stress measurements with high spatial resolution. In each sensor there is a whole matrix of sensing cells. The sensor with 24 sensing cells is used in the test, being placed in two 4 × 4 array. The cells in the corners of 4 × 4 arrays are inactive. The X-Ray image of sensor used in this study is shown in Fig. 1, where cell placements are marked with numbers.

The silicon die is packaged in a standard microelectronic LGA package, which is widely used to encapsulate a Hall sensor. Construction of the package is presented in Fig. 2. The silicon die is attached to a PCB using a die attach adhesive. Electrical connections are formed by wire bonds. There is also a dummy ceramic component soldered on the PCB. The whole construction is overmolded with commercially available epoxy molding compound. The final dimension of the package is 3 mm × 3 mm × 1 mm.

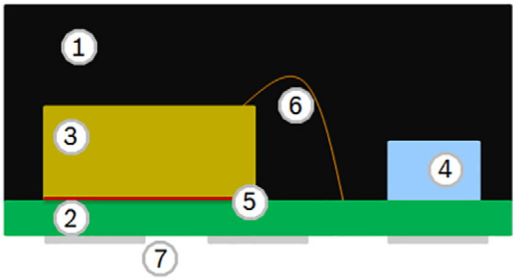

Fig. 2. Construction of LGA Package. 1 – mold, 2 – PCB, 3 – stress sensor, 4 – ceramic, 5 – die attach, 6 – wire bond, 7 – soldering pads.

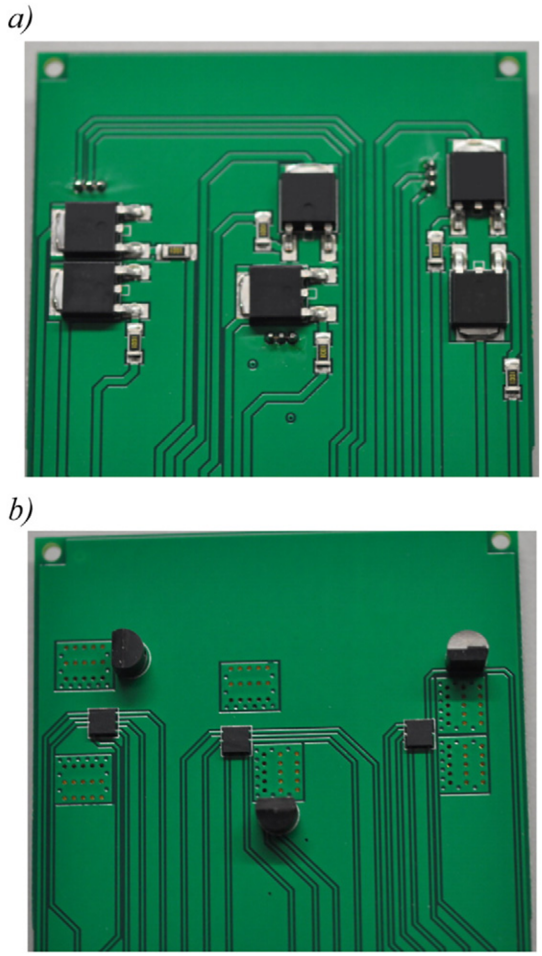

Fig. 3. Test vehicle a) top side view b) bottom side view.

3. Test vehicle

The test vehicle with stress sensors is a four full copper layer PCB containing six DPAK packages on one side (Fig. 3a) and three stress sensors on the other (Fig. 3b). This test vehicle is designed for reliability testing in which data acquisition from the sensors continues until the failure occurs.

The DPAK packages are placed in pairs at three different positions on the PCB. Two pairs are located along the edges of the PCB. The DPAKs within these two pairs have different relative orientations and the orientation toward the edges of PCB. The goal of this design is to

Table 1
Material properties.

Material properties considered in the simulation		Modulus of elasticity [MPa]	CTE [ppm/K]	Material law
DPAK	Copper lead frame	125,000	17	*Linear-elastic*
	Solder	49,551	20	*Viscoplastic*
	Silicon die	167,000	8	*Linear-elastic*
	Molding compound	17,000	12	*Viscoelastic*
PCB	Copper (PCB traces)	80,000	17	*Linear-elastic*
	Prepreg	24,000	14	*Viscoelastic*
Stress sensor	Substrate	23,000	19	*Homogenized*
	Adhesive	8000	51	*Viscoelastic*
	Silicon die	167,000	8	*Linear-elastic*
	Molding compound	26,000	8	*Viscoelastic*