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Comparison of analysis methods for package-induced stresses on moulded Hall sensors

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Abstract Due to the piezoresistive and the piezo-Hall effect in semiconductor materials, Hall sensors show a strong temperature dependency and also a drift when subjected to temperature cycles Manic et al. (2000). Four factors mainly influence the mechanical stress in the sensitive layer. These are the geometry of the device, the differences of the coefficients of thermal expansion of the package materials, the temperature-dependent material properties and the time-dependent, viscous material properties. The objective of this investigation was to determine the mechanical stress in a moulded Hall sensor during the packaging process by finite-element simulation in comparison to experimental methods. It is shown that after each process-step the mechanical stress in the sensitive layer changes over time depending on the absolute value and the rate of the temperature change. Measurements of the inverse bending radius of glued and moulded chips show good agreement to the simulations.

1 Introduction

Hall sensors are widely used for position detection. Especially in automotive applications the requirements to the sensor device are rather high regarding the offset and sensitivity accuracy over a large temperature range. Due to the piezo properties of the Hall layer the sensors are very sensitive to mechanical stress, which will alter the offset and the sensitivity of the device significantly. Stress leads to a change of the resistivity of the Hall plate. If the current through the Hall plate and the mechanical stress are not parallel, the mechanical stress also leads to an offset voltage, which is known as pseudo-Hall effect (Hälg 1988). Stress in the device results from differences in the coefficient of thermal expansion of the package materials and the temperature- and time-dependent material properties. When the device is exposed to a temperature change, the described material behaviour leads to stresses and shape changes of the device. The bending radius is one measure for the stress-state within the device. For crystalline materials, like silicon, deformation can be measured by X-ray. This gives the possibility to verify the simulation results. In this paper we report on the progress of the research project “The Influence of Package-Induced Stresses on Moulded Hall Sensors”, (Fischer et al. 2005).

2 Assembly of hall sensors

A typical Hall sensor consists of a silicon chip, carrying the Hall plates and the electronic circuits for signal conditioning. The silicon chip is conductively glued on a leadframe and encapsulated by an epoxy-moulding compound. Figure 1 shows an unmoulded and a moulded Hall sensor device.

3 Simulation

Simulations were performed to analyse the influence of the packaging process, whereas several temperature steps occur, on the stress in the top silicon layer. From drawings and microsection pictures a three dimensional FE-model was built for the simulation. As a basis for modelling the materials in the package correctly, dynamic mechanical analysis (DMA), thermal mechanical analysis (TMA) and creep tests were performed on the moulding compound and on the adhesive Deier and Wilde (2000). With these measurements the elastic properties, such as the coefficient of thermal expansion (CTE) and the Young’s modulus as well as the visco-

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elastic properties of the moulding compounds and the adhesives were determined (Fischer et al. 2005). With the performed simulations, the stress in the silicon top-layer was investigated. To verify the simulation results, an experimental investigation was performed. The inverse bending radius is a goof measure for the stress-state of unsymmetric assemblies. According to Eq. 1 the thermomechanical stress σ_i for layer i in a structure comprising three layers of different materials is generally given by (Iancu 1989):

$$\sigma_i(z_i) = \frac{E_i}{1 - \nu_i}\left(\varepsilon_i^0 + \frac{z_i}{R} - \alpha_i \Delta T\right), \tag{1}$$

where

E_i	Young's modulus of layer i
ε_i^0	strain of the centre plane of layer i
R	bending radius of the entire structure
α_i	CTE of layer i
z_i	distance in height to the centre of layer i
T	temperature
ν	Poisson ratio

3.1 Simulation of the assembly and packaging process

During the processes of assembly and packaging the sensor device can be exposed to very high mechanical stress. This mechanical stress results from differences in the coefficients of thermal expansion of the materials and large temperature differences over the complete assembly and packaging process. Furthermore the geometry and the temperature- and time-dependent material properties have a strong influence on the stress in the Hall plate. The temperature profile of a typical assembly and packaging process including the process steps glue-curing, moulding, mould-curing, electroplating and an optional final test is displayed in Fig. 2. The backend-process starts with gluing the silicon chip on the leadframe. For glue-curing the device is heated up to 145°C. At that temperature the adhesive exhibits a very low Young's modulus. Thus, the device is assumed to be stress-free. While cooling down, the Young's modulus of the adhesive rises especially below the glass transition temperature at 80°C, Fig. 3. Due to the higher coefficient of thermal expansion of the leadframe compared to the silicon, the silicon bends to a convex shape and a tensile stress of about 80 MPa is induced in the top layer of the silicon chip (Fig. 4.1). During moulding the device is heated up again to 180°C. This thermal step induces a compressive stress of −20 MPa in the top silicon layer. After moulding, the device is cooled down to 25°C again. Due to the surrounding moulding compound, which exhibits a relatively high coefficient of thermal expansion, a very high compressive stress of almost −100 MPa is induced in the silicon top layer.

Furthermore, it can be seen that as we are taking the viscoelastic behaviour of the moulding compound into account the stress is not constant over time at each isothermal fabrication step. During mould-curing the stress in the viscoelastic simulation is lower compared to the linear-elastic case. Over time, the stress in the viscoelastic case rises and approaches the stress value of the linear-elastic case. This behaviour results from an increasing deformation of the silicon due to the viscoelastic backcreep of the moulding compound, especially at high temperatures. Qualitatively the same behaviour can be seen during the electroplating and the final test, Fig. 5.

The increasing bending of the silicon during the isothermal mould-curing process is shown in Fig. 6. Due to the strong stress-dependency of the output signal of the sensor, the offset and the sensitivity of a Hall sensor device change over time at constant temperatures. This behaviour cannot be compensated by conventional temperature-compensation methods.

During the mould-cure at 180°C the inverse bending radius of the silicon chip increases. This leads to an increasing stress in the silicon chip Fig. 6. The inverse

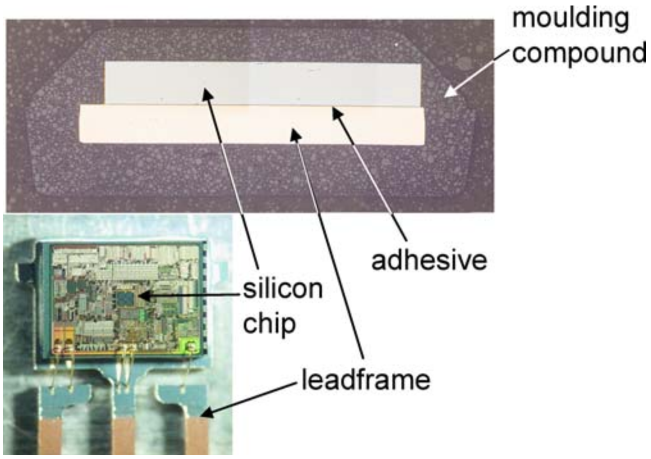

Fig. 1 Unmoulded and moulded Hall sensors

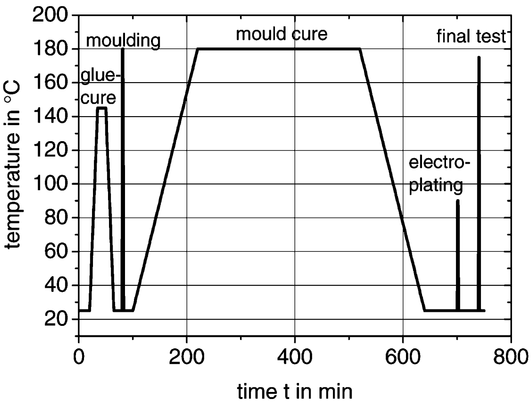

Fig. 2 Typical temperature profile during the assembly and packaging process of moulded sensors

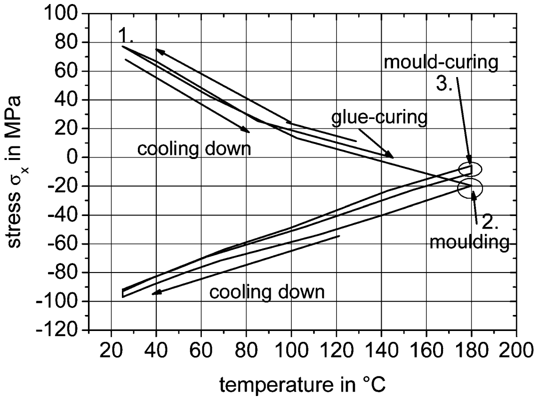

Fig. 3 Computed temperature-dependent stress σ_x in the sensitive area of the silicon chip

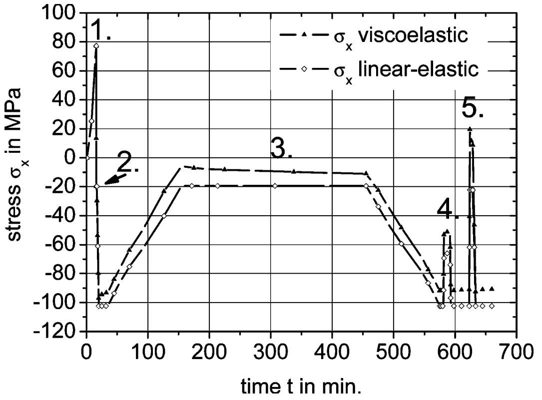

Fig. 4 Computed stress σ_x in the sensitive area of the silicon chip during the backend-process; *1* after glue-curing, *2* moulding, *3* mould-curing, *4* electroplating, *5* final test

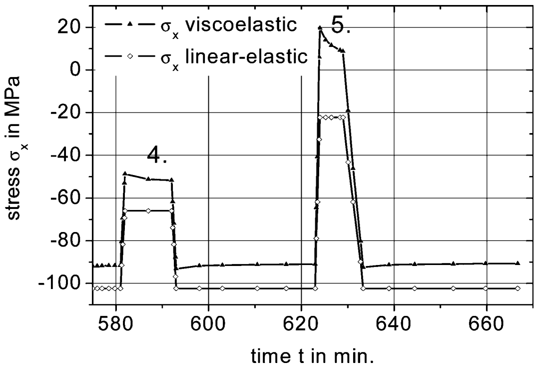

Fig. 5 Computed stress σ_x in the sensitive area of the silicon chip during the electroplating and the final test

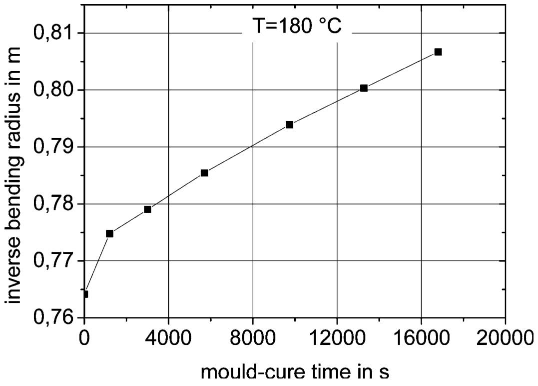

Fig. 6 Inverse bending radius of the silicon during the mould-curing process at $T = 180$°C, FE-simulation

bending radius is proportional to the stress in the considered layer Fig. 4.3.

4 Measurements and discussion

Measurements of the temperature- and stress-dependent offset voltage and the sensitivity of the Hall sensor device were performed. To verify the simulation results the bending radius of the unmoulded and moulded silicon chip were measured using a white-light interferometer and X-ray methods.

4.1 Electrical measurements

To measure the stress- and temperature dependency of the offset voltage of a typical semiconductor Hall plate, a device with a chip size of 100×100 µm was loaded with different constant temperatures and mechanical stresses. For this purpose a three-point bending fixture was built and placed in an oven. No magnetic field was applied to the device. The device was operated with a current of 0.1 mA. At each temperature the offset voltage for different values of the mechanical stress was measured. The performed measurements demonstrate the strong temperature- and stress dependency of the offset voltage, Fig. 7. The measurements show an approximately linear increase of the offset voltage with rising temperature. Also an increasing temperature dependency with increasing mechanical stress is obvious.

The stress sensitivity changes by approximately +45% in the temperature range from 25 to 175°C.

Both the stress- and the temperature dependency of the offset voltage are described approximately by Eq. 2.

$$U_{\text{offs}} = \frac{103\ \mu\,\text{V}}{178\,\text{MPa}} \times \sigma \times \left(1 + \frac{0.45}{150\,K}\Delta T\right) \tag{2}$$

with a reference temperature of $T = 25$°C.

Consequently an offset voltage of 50–60 μV must be expected in the device after moulding.

4.2 Measurements of the bending radius

To measure the bending radius of the silicon chip, white-light interferometer measurements were performed on the chip glued on the leadframe, Fig. 8. The contact

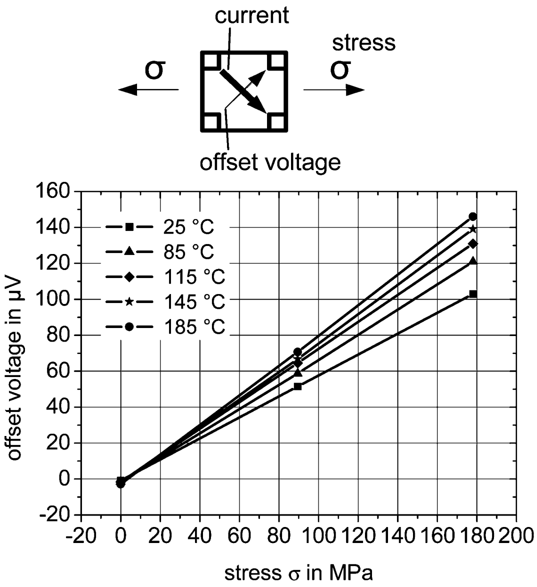

Fig. 7 Measured offset voltage of a Hall plate as a function of mechanical stress and temperature

structures between the Hall plates were removed because of their very different light-reflection behaviour. The measurements of the bonded chip were performed with a Zygo LOT NewView 5022. They reveal a bending radius in the centre of the chip of $R_b = 280 \pm 20$ mm, Fig. 8. On the edges of the Hall plates at a distance of 0.1 mm a radius of $R_b = 330 \pm 25$ mm was measured.

Furthermore, X-ray measurements were performed and compared to simulation results. These have been carried out at the 'Institut Fresenius' Laboratories, Dresden.

With X-ray measurements it is possible to measure the inverse bending radius of the top silicon layer directly inside the moulded package. The measurements were performed at 25°C on a bare silicon chip, on a chip glued on the leadframe and on a moulded device. On the bare silicon chips almost no bending radius could be measured. Figure 9 displays the inverse bending radius of the chip glued on the silicon. In the centre part where the Hall plates are situated, the measurements and the simulations show good agreement.

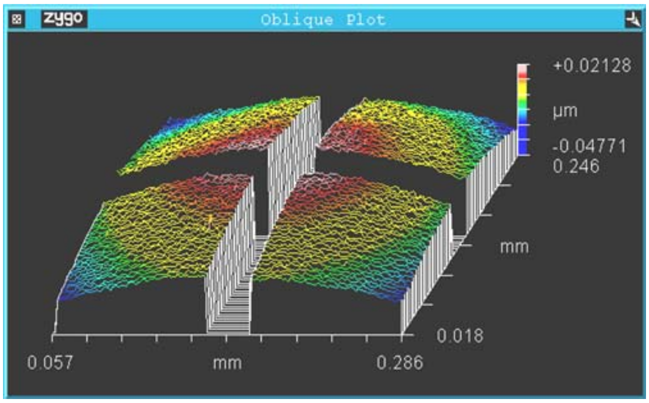

Fig. 8 Measured deformation of the Hall plates performed with a white light interferometer, silicon chip glued on the leadframe

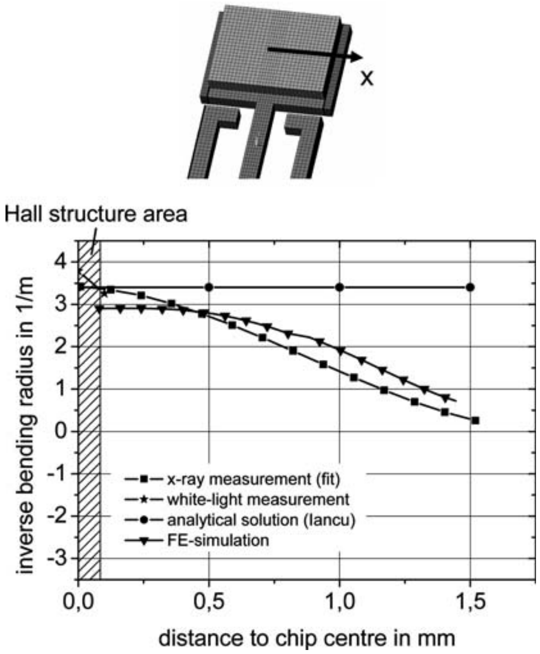

Fig. 9 Measured and computed inverse bending radius of the silicon chip glued on the leadframe, viscoelastic simulation, $T = 25°\mathrm{C}$, *x*-direction

The inverse bending radius of the entire device is much lower than the bending radius of the chip glued on the leadframe, Fig. 10. The higher stress in the silicon after the moulding, Fig. 3, compared to the stress after glue-curing is a result of high compressive stress portion in the silicon due to the surrounding moulding compound. The moulding compound constrains the glued chip in bending. Thus, the bending radius is higher and consequently the stress is lower. Due to the high

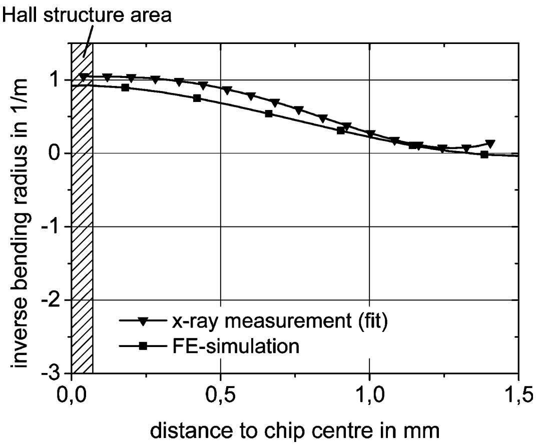

Fig. 10 Measured and computed inverse bending radius of the silicon in the moulded device, viscoelastic simulation, 25°C, *x*-direction

coefficient of thermal expansion of the moulding compound a high compressive stress is induced in the device when it is cooled down.

5 Conclusion and outlook

The performed measurements demonstrate the strong stress dependency of the offset voltage of Hall sensors. The measured and computed bending radii show good agreement. Thus, the deformations and stresses in the unmoulded silicon chip are computed correctly by FE-simulation. After the moulding the compressive stress due to the moulding compound has the major influence on the stresses in the silicon chip. Because of the visco-elastic material behaviour these stresses are nonlinear over time. When the material behaviour is known and the fabrication process for moulded sensors is computed precisely, the stresses in the silicon chip can be calculated correctly. Furthermore, effects like zero-point drift and sensitivity-drift over temperature cycles can be explained.

Both, the simulations and the experiments demonstrate that for correct modelling and simulation of the package-induced stresses, it is indispensable to take the time- and temperature-dependent material properties into account. Especially for sensors working in harsh environment and if high temperature changes occur the time-dependent material behaviour will lead to offset and sensitivity drifts which are not negligible. Already during the assembly and packaging process of sensors very high stresses are induced into the sensitive layer. For optimisation of the accuracy, the thermo-mechanical stresses have to be modelled correctly.

The differences of the measured results compared to the simulations of about 25% can be explained by the complex material behaviour including the shrinkage of the moulding compound. Further work will be done to characterise the shrinkage and also the viscoplastic creep behaviour of moulding compounds. Also measurements will be performed to analyse the sensitivity change of Hall devices under thermo-mechanical loadings.

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