

Analysis of the Influence of Packaging Stresses on the Accuracy of Hall Sensor ICs

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Abstract:

The offset and the sensitivity of semiconductor Hall sensors show a strong temperature-dependency and also a drift when subjected to temperature cycles. This behaviour is a result of the sensitivity of the piezo-resistive effect and the piezo-Hall effect of the implanted Hall layer on mechanical stress. Mechanical stress is mainly caused by differences in the coefficient of thermal expansion of the package materials and is also affected by time-dependent, viscous materials properties. The objective of this investigation is to analyse the mechanical stresses in a moulded Hall sensor during the backend-process by simulation. Additionally the conditions for modelling the process of packaging correctly and its influence on the sensor's performance must be analysed. The time- and temperature-dependent properties of a moulding compound were measured and taken into account during the simulation. Compared to linear-elastic simulations, the strong influence of the moulding compound on the time- and temperature-dependent stresses in the sensitive Hall layer is presented. The stress and consequently the output signal of the sensor exhibit hysteresis over temperature cycles. The simulations were calibrated and validated with experimental results. Measurements of the bending radius of bare chips, silicon chips glued on the leadframe and moulded devices were performed by x-ray techniques. These and additional interferometer measurements show good agreement with the simulation results.

1. INTRODUCTION AND THEORY

Hall sensors are widely used for position detection. Especially in automotive applications the requirements to the sensor device are rather high regarding offset and sensitivity accuracy over a wide temperature range. Due to the piezo properties of the Hall layer the sensors are very sensitive to mechanical stress, which will change the offset and the sensitivity of the device significantly. The relation between the electric field \vec{E} , the current density \vec{J} and the magnetic flux density \vec{B} in a cubic crystal like silicon can be expressed as [1,4]:

$$\vec{E} = \rho \vec{J} - (R_H \vec{B}) \times \vec{J} \quad (1)$$

where R_H and ρ are the Hall coefficients and the specific resistance respectively. Both are functions of the mechanical stress within the sensitive layer. Their relative changes are defined by

$$\frac{\Delta \rho_{ij}}{\rho_0} = \sum_{kl} \pi_{ijkl} \sigma_{kl} \quad \text{and} \quad \frac{\Delta R_{ij}}{R_0} = \sum_{kl} P_{ijkl} \sigma_{kl} \quad \text{with } i, j, k, l = 1..3 \quad (2)$$

where σ_{kl} is the tensor of the mechanical stress, π_{ijkl} and P_{ijkl} are the piezoresistive and the piezo-Hall coefficient tensors respectively. Thus, mechanical stress leads to a change of the specific resistance of the Hall plate. If the current through the Hall plate and the mechanical stress are not in parallel, the mechanical stress also leads to an offset voltage which is known as pseudo-Hall effect.

2. ASSEMBLY OF MOULDED HALL SENSORS

A typical Hall sensor contains the silicon chip which is bonded on a leadframe by a conductive adhesive and moulded into an epoxy moulding compound. Fig. 1 displays a FE-model of a leaded Hall sensor package. The ion-implanted Hall plate is found in the top layer of the silicon chip.

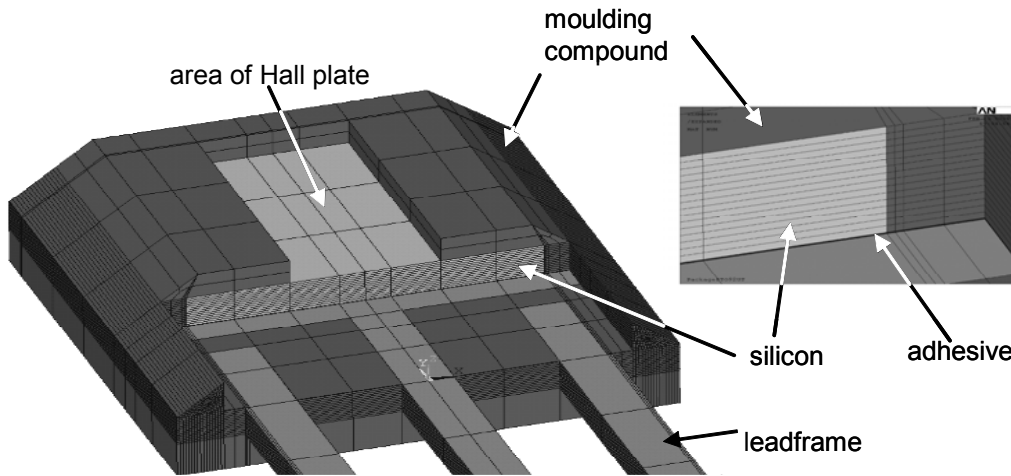


Fig. 1: FE-model of a moulded Hall sensor in a leaded package, PTO-type

Typical data for materials, taken from several sources are given in Tab. 1.

Material	Young's modulus in GPa	CTE α_1 in K^{-1}	CTE α_2 in K^{-1}
silicon	165	$2 \cdot 10^{-6}$	
conductive adhesive	7.5	$65 \cdot 10^{-6}$	$135 \cdot 10^{-6}$
leadframe	133	$17 \cdot 10^{-6}$	
moulding compound	20	$12 \cdot 10^{-6}$	$40 \cdot 10^{-6}$

Tab. 1: α_1 and α_2 are the coefficients of thermal expansion below (1) and above (2) the glass transition temperature

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. For modelling the materials in the package correctly, DMA (Dynamic Mechanical Analysis), TMA (Thermal Mechanical Analysis) and creep tests were performed on the moulding compound and on the adhesive [2]. With these measurements the elastic properties, such as the temperature-dependent coefficient of thermal expansion and the temperature-dependent Young's modulus as well as the viscoelastic properties of the moulding compounds and the adhesives were determined. The viscoelastic material behaviour was modelled using a Prony series.

3.1 Simulating the Packaging Process

During the backend-process the sensor device is 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 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 backend process including the process steps glue-curing, moulding, mould-curing, electroplating and an optional final test are displayed in Fig. 2.

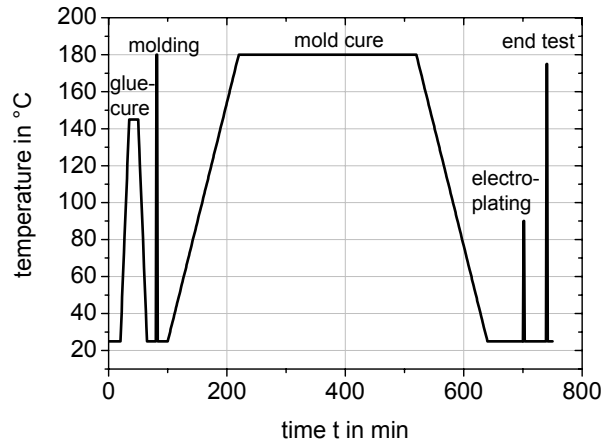


Fig. 2: typical temperature profile during the backend-process of moulded sensors

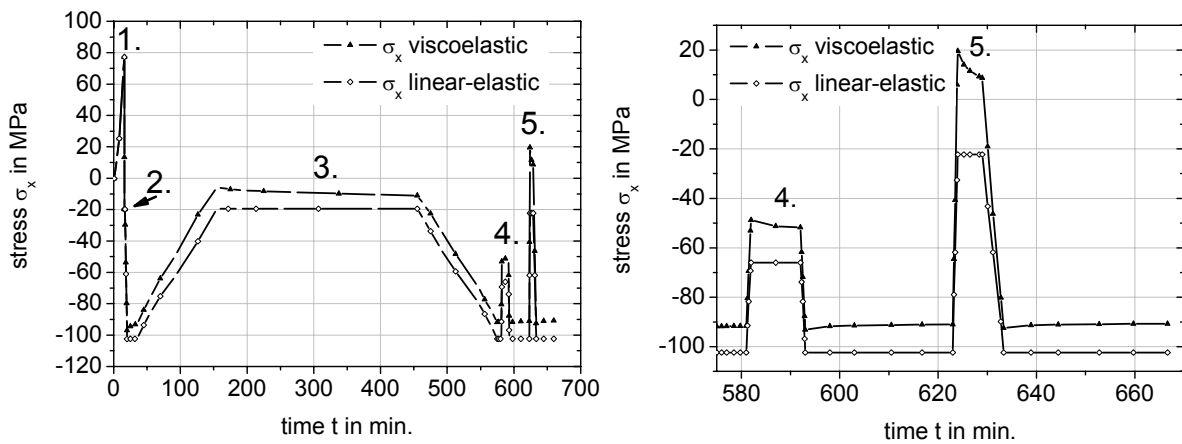


Fig. 3: simulated stresses σ_x in the Hall plate over the backend process; 1 glue-curing, 2 moulding, 3 mould-curing, 4 electroplating, 5 final test (optional)

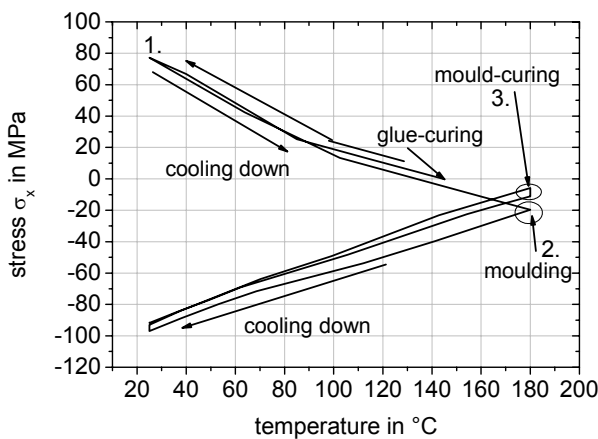


Fig. 4: temperature-dependent stresses σ_x in the Hall plate during the backend-process

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. Due to the higher coefficient of thermal expansion of the leadframe compared to the silicon the silicon bends convex and a tensile stress of about 80 MPa is induced in the top silicon layer (Fig. 3, 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 top silicon layer. Furthermore it can be seen, that when 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 low 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 creep behaviour of the moulding compound, especially at high temperatures. Qualitatively the same behaviour can be seen during the electroplating and the final test.

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. The analysis of the stress-sensitivity is described in the next paragraph.

4. MEASUREMENTS AND DISCUSSION

Here the temperature- and stress-dependent offset voltage of a typical Hall plate was measured, for verifying the simulation results. Also measurements of the bending radius of the silicon chip were performed at room temperature.

4.1 Hall Sensors under Thermo-Mechanical Loading

For measuring the stress and temperature-dependency of a typical semiconductor Hall plate, a device with a chip size of 100 x 100 µm was loaded with different constant temperatures and mechanical stresses. No magnetic field was applied to the device. The device was operated with a current of 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. 5.

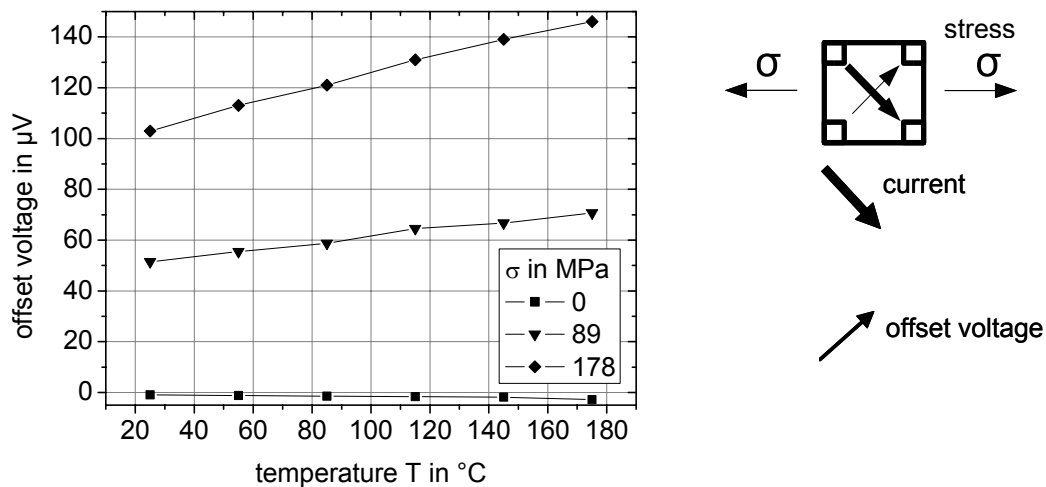


Fig. 5: offset voltage of a Hall plate as a function of temperature and mechanical stress

The measurements show an approximately linear increase of the offset voltage with rising temperature. Also an increasing gradient of the temperature-dependency with increasing mechanical stress is seen. The stress sensitivity changes by approximately +45 % in the temperature range from 25 °C to 175 °C. Both the stress- and the temperature-dependency of the offset voltage are described approximately by:

$$U_{offs} = \frac{103 \mu V}{178 \text{ MPa}} \cdot \sigma \left(1 + \frac{0.45}{150 \text{ K}} \Delta T \right) \text{ for a reference temp. of } 25 \text{ } ^\circ\text{C} \quad (3)$$

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

4.2 Bending Radius

For measuring the bending radius of the silicon chip white-light interferometer measurements were performed on the chip glued on the leadframe, Fig. 6. The contact structures between the Hall plates were removed because of their very different light-reflection behaviour. If no compressive stress is present, the inverse bending radius is directly proportional to the stress in the considered layer [8].

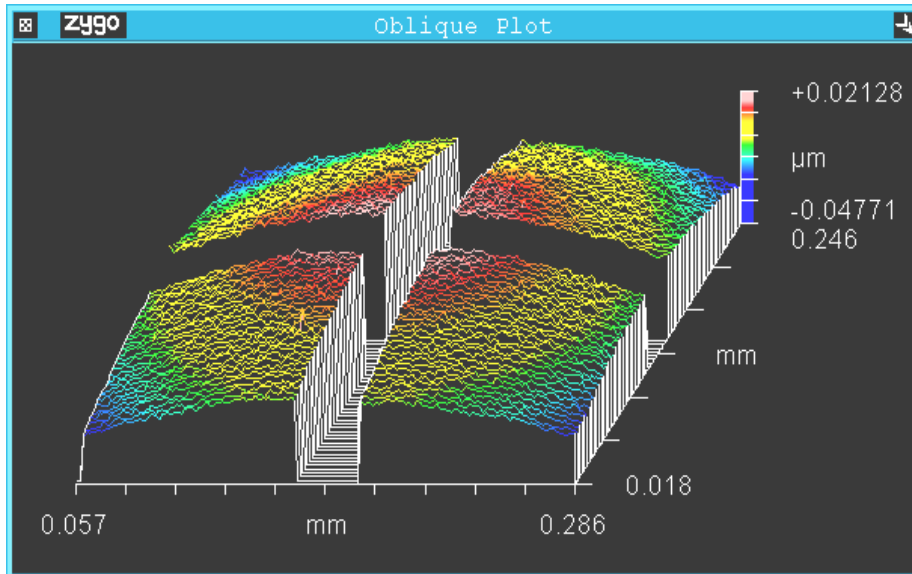


Fig. 6: measured deformation of the Hall plates at 25 °C performed with a white light interferometer, silicon chip glued on leadframe

The white-light interferometer measurements of the bonded chip, performed with a Zygo LOT NewView 5022, display a bending radius in the centre of the chip of $R_b=280\pm 20$ mm. At 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, a chip glued on the leadframe and a moulded device. On the bare silicon chips almost no bending radius could be measured. Fig. 7 displays the inverse bending radius of the chip glued on the silicon (left) and the moulded device (right). In the centre part of the silicon chip, where the Hall plates are situated, the measurements and the simulations show very good agreement. The bending radius of the entire device is much lower than the bending radius of the chip glued on the leadframe. The higher stress in the silicon after the moulding compared to the stress after glue-curing is a result of the high compressive stress in the silicon due to the surrounding moulding compound.

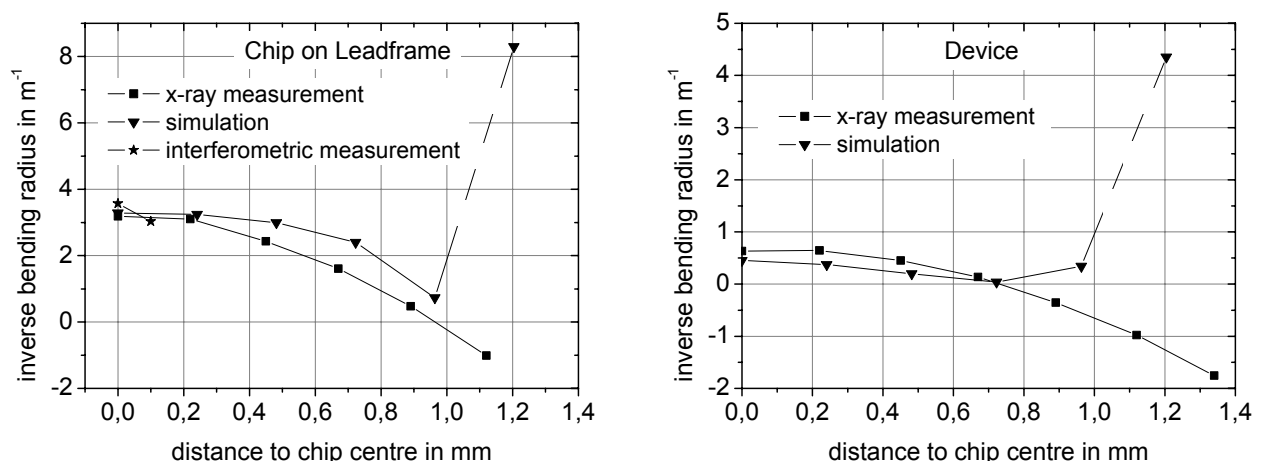


Fig. 7: measured and computed inverse bending radius of the chip glued on the leadframe and the device, T = 25 °C. Viscoelastic simulation.

The high bending radius at the edge of the chips is mainly considered as a result of the singularity at the materials transition from the silicon chip to the moulding compound in the simulation.

5. CONCLUSION AND OUTLOOK

The performed measurements demonstrate the strong stress-dependency of the offset voltage of Hall sensors. The measured and simulated bending radii show good agreement. Thus, the deformations and stresses in the unmoulded silicon chip are correctly computed 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 viscoelastic material behaviour these stresses are nonlinear over time. When the material behaviour is known and the fabrication process for moulded sensors can be simulated 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.

Further work will be done to characterise the viscoplastic creep behaviour of moulding compounds. Also measurements will be performed to analyse the sensitivity change of Hall devices under thermo-mechanical loadings.

6. ACKNOWLEDGEMENT

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