Applications/Metrology

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Microsensors for Automotive Applications – Metrology and Test

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ABSTRACT

According to market surveys automotive microsensors will evolve into a multi-billion dollar business by 2005. Key roles are attributed to inertial sensors for passenger safety systems, and mass flow and pressure sensors for engine management systems. Thin film techniques together with silicon bulk or surface micromachining have been established as preferential processes to achieve reduction of sensor size, weight and cost along with improvements of sensor functionality and reliability. Enhanced sensor performance often pushes the limits of process technology and therefore the need arises very early in the MEMS design process to identify materials and geometry related parameters which are critical with respect to their tolerance band specifications. In order to control these critical parameters, automated wafer level test procedures need to be developed (based preferentially on electrical quantities) and additionally considered for in the sensor design phase (design for test). In analogy to microelectronics 2D wafer maps of critical parameters may give hints on how to improve process stability and how to adapt the sensor design in order to optimize yield. Examples of critical model parameter variations include thermal conductivity, thickness, and shear modulus of thin films.

INTRODUCTION – AUTOMOTIVE SENSOR MARKET

Sensors are enabling components for the functionality of an ever increasing number of electronic systems in the car. Especially for engine emission control and passenger safety systems, microsensors have taken over a large share of the market volume and are beginning to penetrate into the convenience equipment sector. Among these acceleration sensors, gyros, pressure and mass flow sensors are manufactured today efficiently in very large volumes taking advantage of MEMS batch process technologies. Figure 1 shows examples of MEMS transducer elements (dies) and their corresponding packages.

It is believed [1] that automotive microsensors in general will take a market share of 30% by 2005 corresponding to a market volume of almost 3 billion dollars. However, requirements to be met in the automotive market are severe. Demands for increased sensor performance and tightened functional tolerance specifications (sensitivities, resolution, self-test capability, EMI, overvoltage, reverse polarity and EMI protection, ...) have to be met, aiming at reduced cross sensitivities, time constants, noise levels, reduced weight, size and power consumption simultaneously.

In addition reliability of sensor performance has often to be guaranteed within 1% over the lifetime of an automobile, and thus provisions have to be made for the sensor system to

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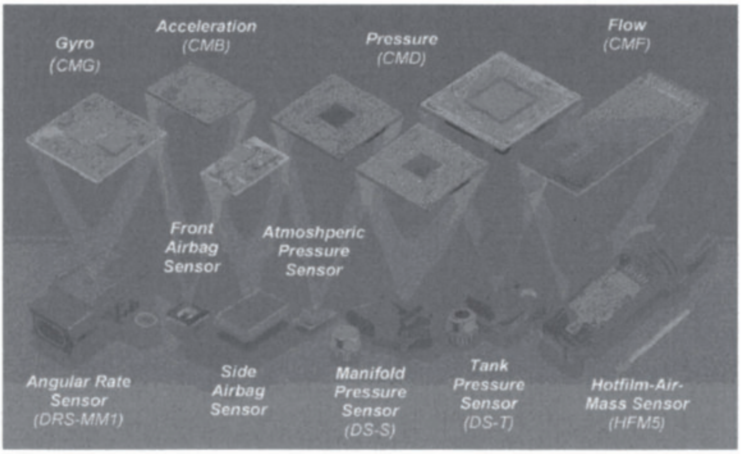

Figure 1. Examples of automotive microsensors.

withstand the corresponding adverse and unfavourable environmental impacts: temperature (-40°C to 125°C) and mechanical (30g) shock, vibration, relative humidity up to 85%, salt spray conditions. At the same time, field failure rates of 10ppm must not be exceeded. Most demanding, however, is the fact, that above performance requirements have to be met at market conform cost levels often characterized by annual price reductions of several percent.

In order to establish MEMS technology as a preferred production technique for automotive sensors, a systematic integral approach to sensor design is indispensable including the development of refined test methods to adequately control MEMS processes with respect to compatibility of geometry and materials parameters with their designed specifications.

MEMS PROCESSES FOR AUTOMOTIVE SENSORS

Over the past decade MEMS technology has evolved from a niche technology into an important mainstream technology for a wide range of applications [2 - 4]. For automotive sensors silicon bulk and surface micromachining have clearly led the way to MEMS commercialization representing a core capability of the automotive supply industry [5-7] . While integration of micromechanical structures into signal evaluation ICs was very successful, e.g. for silicon pressure sensors, „two chip options“ still prevail for applications like mass flow meters and inertial sensors. As a prominent member of the automotive MEMS technology portfolio classical thin film technology is widely used for e.g. (piezo-) resistive, thermoelectrical or magnetic (XMR) transducers.

It is obvious that not all of the proposed MEMS technologies and processes in literature are equally attractive for a single business sector like automotive sensors. Depending - among others - on the existing product portfolio and existing core capabilities, preferential MEMS processes have to be carefully identified (and scrutinized continuously): as many processes as necessary to cover all major applications, as few as possible to meet cost and quality targets.

A common feature in many advanced MEMS functional designs is that geometrical dimensions of MEMS functional structures approach the scale of microstructure variations of the MEMS material used. Large surface to volume ratios and increased influence of local microstructure variations may lead to geometry dependent materials parameters which then differ significantly from bulk values and depend increasingly on process parameters. In addition, new drift phenomena may possibly affect device reliability. This increases the requirements for process control and may complicate the design of a MEMS device to be safe within the functional tolerances specified. Against this background automated test procedures for the precise determination materials parameters will gain in importance.

DESIGN METHODS AND TEST

As outlined above, a MEMS-based sensor for automotive applications needs to be designed to a set of specifications of function parameters (FP). These include sensitivity (S), cross sensitivities , temperature coefficients of sensitivities (TCS), offsets (TCO) nonlinearities of TCS and TCO, resolution, hysteresis and others like reliabilty parameters (see also left side figure 2). In addition every function parameter is related with a specific tolerance band, i.e. an upper and lower limit of acceptance.

Whatever physical signal conversion principle is chosen, the set of functional parameters (FP_i) is determined by a set of model parameters (MP_j) describing the three dimensional geometry and the materials properties of the MEMS device under consideration:

$$FP_i = f(MP_j) \tag{1}$$

The physical relations (models) of the "functional matrix" defined by equation 1 may be quite simple for the bending of a cantilever beam or rather complicated for a resonating rotational disc gyro including viscous damping effects in the surrounding medium. If the physical relations are too complicated for analytical description, FE studies or numerical network analysis have to be used and verified.

After all model parameters are process dependent, i.e. materials and geometry parameters may depend on wafer position and equipment performance (possibly subject to all kinds of involuntary changes and drifts especially during the ramp up of newly developed processes). For a good MEMS design the distribution of these model parameters within their tolerance band (including c_{pk} values) must be known exactly from process monitoring and statistical process control. In order to identify critical model parameters whose process induced fluctuations might drive functional parameters out of their specification range a factorial analysis (i.e. an influence strength analysis) is appropriate.

We define [8] the strength of influence EFS_{ij} of a model parameter MP_j on a function parameter FP_i as

$$EFS_{ij} = \frac{\frac{\partial FP_i}{\partial MP_j} \cdot \Delta MP_j}{\Delta FP_i} \tag{2}$$

$$EFS_j = \sqrt{\sum_i \left(EFS_{ij}\right)^2} \tag{3}$$

where ΔMP_j and ΔFP_i in equation 2 represent the tolerance bandwidths of model parameter MP_j and function parameter FP_i respectively. In the case of significant nonlinear relationships of FP_i and MP_j higher order derivatives have to be used. If mechanical or electronic trimming of a function parameter is feasible ΔFP_i represents the capture range of trimming.

Equation 3 allows for a classification of the influence strengths of various MP_i on a single FP_j. $EFS_j > 1$ represent supercritical variations of geometry or material parameters in the sense that design and/or process technology needs considerable improvement. For $EFS_j = 1$ most specimen (i.e. 99.73% if Gaussian distributions of MPs are assumed) are designed to be within the specs of function parameter FP_j. Safe designs are characterized by $EFS_j < 1$

If yield losses are to be reduced to the order of several ppm and/or sensitivity or resolution specs are to be improved considerably, quite a few critical geometry and materials parameters may show up in an EFS analysis. This necessitates high throughput testing of these model parameters as a "quality gate" in the MEMS production process. Obviously this has to occur at the earliest possible stage of value-adding, i.e. on wafer level, in order to eliminate defective devices before they are packaged. To this end highly automated IC test equipment is used. Since commercially available high throughput probers which could additionally apply primary sensor input signals (yaw rate, pressure, mass flow, …) are nowhere in sight, one is left with purely electrical stimuli for MEMS sensor devices under test. This is the reason why the availability of purely electrical methods for rapid determination of geometrical and materials properties is so important.

If the physical signal conversion principle is reversible (e.g. capacitive), the sensor device may be used for critical model parameter testing (eg. by applying electrostatic actuation) However this may not yield the necessary test precision and will require careful "design for test" in order not to jeopardize sensor function. As an alternative, specially designed test structures dedicated to rapid (and precise) determination of critical material and geometry parameters may be run alongside with sensor devices on a production wafer. When introducing a newly developed MEMS process step, test structure wafer maps might give valuable hints for improving process parameters.

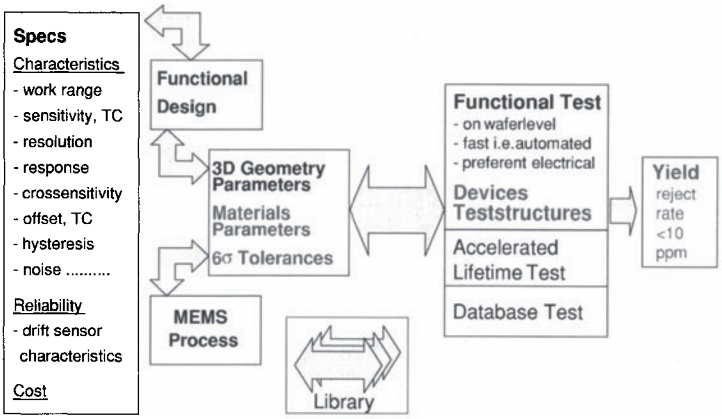

Figure 2. Essential building blocks for microsensor metrology.

Correlating the respective databases of test results, in-process monitors and process parameters will allow rapid (i.e. focused) trouble-shooting and may eventually reduce the number of tests performed. Figure 2 shows an schematic chart of characteristic features of microsensor metrology and test.

EXAMPLES FOR MICROSENSOR METROLOGY AND TEST

Mass Flow: Thermal Conductivity

Calorimetric principles have been widely used to measure mass flow in automotive air intake systems. Since 1995 bulk micromachining technologies were able to reduce size and cost considerably [6]. In general a thin film heater is placed symmetrically between two thermoresistors on a thin SiON membrane resembling a thermally isolated micro hot plate. Mass flow density and direction of flow is determined from the temperature difference of the thermoresistors.

It is obvious that the thermal conductivity is an important material property for the design of thermal mass flow sensors. In addition, control of response times within narrow limits requires tight control over the thermal heat capacity of MEMS-materials and multilayer thin film systems. However, thermal properties of thin films have been reported to differ strongly from bulk properties, in addition they might depend significantly on process parameters and location on the wafer. [9-12].

A variety of techniques has been reported both for out-of-plane [13,14] and in-plane thermal conductivity measurements [15,16]. Unfortunately, most techniques are not suitable for high throughput testing of material properties on wafer level in a microfab, especially if vacuum conditions and/or radiation shields are required. However, Cahill et al. reported a technique that fits MEMS test requirements fairly well [17-20]. This so-called 3ω method uses a thin film structure, deposited on the surface of the device under test, serving both as heater and thermometer (fig. 3). A periodic heating current with angular frequency ω is giving rise to temperature oscillations within the thermoresistor. In the sample below this leads to a diffusive thermal wave, whose amplitude ΔT and phase depend on the thermal properties of the substrate and on the frequency. The electrical resistance of the heater itself depends on the temperature and therefore oscillates with angular frequency 2ω. The measured voltage drop

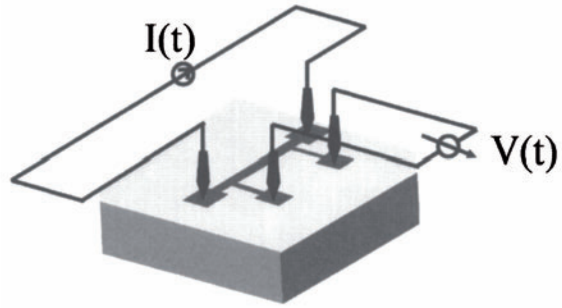

Figure 3. Schematic of thin film pattern to measure thermal material properties (3ω method).

over the thermoresistor thus contains a small component $V_{3\omega}$ with angular frequency 3ω which is detected employing lock-in techniques. Amplitude and phase of this component yield information about the thermal properties. For the evaluation of thermal conductivity the following equation might be used [9]:

$$\Delta T = \frac{P}{l\pi\lambda}\left(-\frac{1}{2}\ln\omega - \frac{1}{2}\ln\frac{ib^2}{D} + \text{const.}\right), \qquad (4)$$

Denominations are as follows: thermal conductivity λ of the substrate, heating power per length P/l, width of the heater 2b and thermal diffusivity $D= \lambda/\rho c$, with thermal capacity c and density ρ. The frequency-dependence of the temperature oscillation is described exclusively by the first term in equation 4, while the imaginary part (i.e. the out-of-phase oscillation) is independent of frequency. Plotting the real (i.e. in-phase) part of the amplitude ΔT versus the logarithm of the heater frequency yields a straight line with a slope proportional to $1/\lambda$. Figure 4 shows the experimental result for a silicon substrate at temperature T = 340 K with a very thin Si_3N_4 electrical insulation layer. Temperature oscillation amplitudes in fig. 4 are calculated from [17]

$$\Delta T = 2\frac{dT}{dR}\frac{R}{V}V_{3\omega}, \qquad (5)$$

where R is the electrical resistance of the heater and V and $V_{3\omega}$ are the measured rms voltages at frequency ω and 3ω, respectively. Using equation (4) and P = 25 mW, l = 0.5 mm one arrives at a thermal conductivity λ = 136 W / m K for the silicon substrate, which is in fairly good agreement with the literature value at this temperature [21].

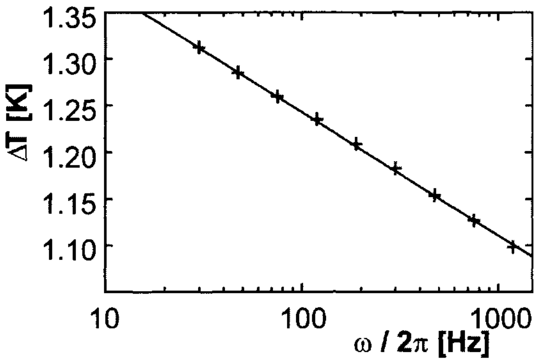

Figure 4. Temperature oscillation amplitudes ΔT as a function of frequency in a bulk Si sample at T = 340 K. Evaluation of thermal conductivity yields λ = 136 W / m K.

This method was first proposed for the determination of the thermal conductivity of a semi infinite substrate and has been extended for the thermal conductivity measurement of thin films and multilayers [18-19]. It is also suitable for measurements of the thermal capacity [17] and, slightly modified, the method can handle even anisotropic thermal conductivity of multilayer thin or thick film systems often encountered in MEMS technologies.
Future generations of mass flow or IR radiation sensors might use porous silicon layers, SiGe or SiC thin films. Then, 3ω structures could provide a tool for state-of-the-art wafer level test of thermal materials properties.

Fluid Condition Monitoring: Materials Properties of SAW Devices

On-board monitoring of liquids such as e.g., engine and gear box oil, diesel and gasoline fuels, brake fluids or battery liquid may gain importance as a future field of MEMS-based sensors. On-board fuel analysis aims at optimizing exhaust gas emissions in case biological based propellants ("alcogas", "biodiesel") should be added to standard grade fuels. On-board oil condition monitoring may lead to prolonged exchange intervals based on actual wear and might reduce consumption drastically. In addition, fluid analysis may open up a new way for early detection of abnormal states of operation of automotive subsystems.

Surface Acoustic Wave (SAW) liquid sensors are working with shear polarized wave modes, generated electrically on piezoelectric crystals such as quartz or lithium tantalate. They have proven to be highly sensitive devices for the determination of density and viscosity of liquids [22 - 25]. High intrinsic stability, extremely low noise floor and simplicity in manufacturing makes them extraordinary suitable for use in automotive applications.

The sensing effect is based on the fact, that a change in density (ρ) and viscosity (η) of the surrounding medium leads to a change of phase velocity (v_p) of a surface wave propagating from the transmitting to the receiving electrode. Interdigital electrode geometries (IDE with periodicity p) lead to an electrical band pass behavior, and with dedicated electronic circuitry the center frequency (f_0) of the device can be determined.

$$f_0 = \frac{v_p}{p} \quad ; \quad \frac{\Delta f_0}{f_0} = S \cdot \sqrt{\rho\eta} \qquad (6), (7)$$

Very good sensitivities S together with a high level of freedom of design can be achieved with LOVE -Mode devices [26] as shown in fig. 5. These modes are shear modes confined

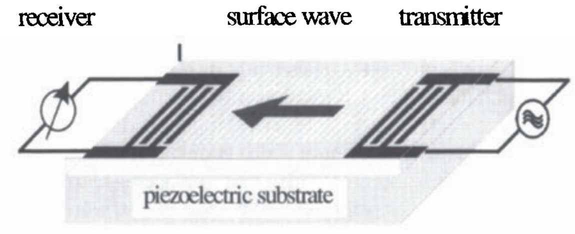

Figure 5. LOVE - Mode surface acoustic wave sensor with acoustic waveguide on interdigtial electrodes.

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Table I. Section of factorial analysis matrix for a LOVE -Mode viscosity sensor.

					Functional Parameters		
					Sensitivity	op. Frequency	
					10^{8} m^2s/kg	MHz	unit
					4,0	119	lower limit
					4,1	120	upper limit
					0,1	1	Δ FP
Model Parameters MP	unit	lower limit	upper limit	Δ MP	Coefficients of Influence EFS		
Shear Modulus G	GN/m^2	2,15	2,17	0,02	0,6	0,3	
Film thickness d	μm	3,95	4,1	0,15	0,6	0,6	

to the crystal surface by an acoustic wave guide, consisting of a dielectric layer with a lower shear wave velocity than the bulk crystal. Due to its mechanical properties and chemical inertness, silicon dioxide deposited by PVD or CVD processes is preferred serving both as waveguide and passivation layer.

EFS factorial analysis (table 1) has been established with simulation results making use of numerical calculation methods described in [26] and [27]. It shows that electrical characteristics and sensitivity performance of a LOVE -mode sensor are mainly determined by thickness and the shear modulus of the silicon dioxide film. These parameters, however, are subject to variations within a wafer or a manufacturing lot leading to variations in sensitivity of the sensor. Calibration of each sensor in liquid at the end of the manufacturing process is not reasonable from an economic point of view.

However the sensitivity of each device can be calculated if the distribution of film thickness and shear modulus over the wafer is known. In order to establish a wafer map of these two parameters conventional optical characterization methods (for determination of film thickness) are too expensive and time consuming. Due to their destructive nature indentation methods for a determination of elastic properties are not appropriate.

An alternative approach based on electrical measurements only and therefore compatible to state-of-the-art wafer testing makes use of the different propagation characteristics of different surface acoustic wave modes. In general the mode of vibration of surface waves is dependent on crystal orientation. This opens up a possibility to excite LOVE-Modes and RAYLEIGH-Modes[1] on the same substrate with propagation direction perpendicular to each other.

A test structure consisting of two crossed delay lines with equal electrode periodicity and distance allows the excitation of both modes. By measuring the transfer function (fig. 6b) the phase velocity of both modes can be determined from equation (5). For a given substrate material and electrode periodicity, there is only one consistent pair of values for shear modulus and film thickness, for which the dispersion relations of both modes are fulfilled. The dispersion relations (fig. 7) were calculated using numerical methods described in [26]. In practice the variation of shear modulus within a single wafer is much smaller than the variation in film thickness. In most cases it is therefore sufficient to place test structures for the determination of shear modulus only at a few representative spots on the wafer (see fig. 6a). Then these values can be used to calculate and monitor film thickness of neighboring devices during wafer test.

[1] For sake of accuracy we should speak of RAYLEIGH-like Modes, as pure RAYLEIGH -modes are not defined for layered structures