Multi-function Microsensor for Oil Condition Monitoring Systems

D. Wüllner[1], H. Müller[1], O. Lüdtke[1], H. Dobrinski[2], T. Eggers[2]

[1]HELLA KG Hueck & Co, Beckumer Str. 130, D-59552 Lippstadt; [2]Campus Micro Technologies GmbH, Universitätsallee 27-29, D-28359 Bremen
[1]dirk.wuellner@hella.com; [2]info@campus-micro-echnologies.de

Keywords: Automotive MEMS, microsystem technology, oil condition, oil level sensor, impedance spectroscopy

1 Abstract

Today's passenger cars provide a very long service interval. Because of this, the monitoring of the oil condition is becoming more important. It is necessary to monitor the oil condition to prevent engine failures as a result of extreme driving conditions, such as when one makes many short trips over a long period. This task can only be reliably realized by means of a sensor located in the difficult environment of the engine oil. As a significant supplier of oil level sensors, Hella developed, in cooperation with its partners, a low cost microsensor (Fig.1b). Based on simulation results, a sensor design was developed and later fabricated by employing standard CMOS-compatible materials and processes. The microsensor allows for the measurement of various electrical and physical parameters. This sensor can provide a significant contribution to the reduction of the running costs of the car. It can also protect the environment through extended oil change intervals by considering driving behaviour. Additionally, damage caused by oil deterioration in sophisticated engines can be prevented [1].

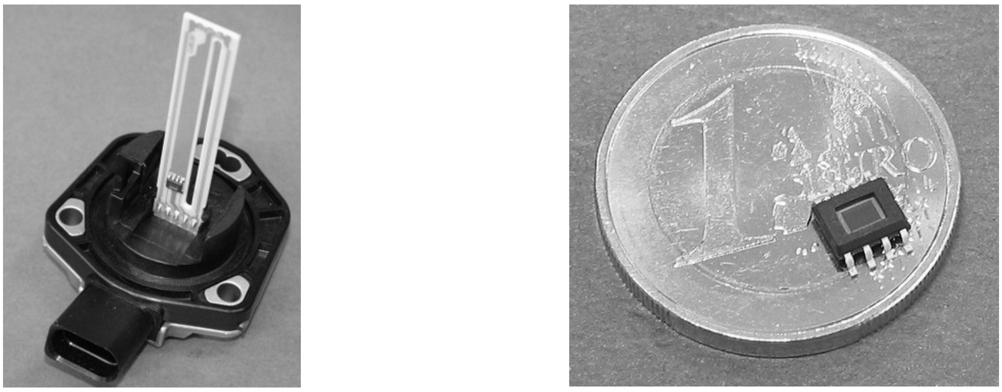


Fig. 1. Fully functional prototype of the oil condition, level and temperature sensor (a); Photo of the microsensor in an open-cavity SOIC-8 package in comparison to a 1€ coin (b)

2 Significance of the paper

The microsystem technology allows for the expansion of oil sensor functionality to provide oil condition monitoring. The focus has been the integration of the packaged sensor into a highly reliable oil level sensor as a stand-alone module with consideration for assembly concerns. A successfully integrated multifunction microsensor in an existing oil level sensor is a revolution in the field of oil applications (Fig.1a). Compared to existing or conventional oil condition sensor principles [2], this microsensor demonstrates the capability for working with multiple measurement principles such as capacitive read-out or impedance spectroscopy. This allows the system to measure the dielectric constant and the viscosity with the same microsensor. A very important factor has been the successful development and integration of the microsystem in the existing automotive sensor design.

3 Sensor design, modeling & fabrication

3.1 Sensor design

The capacitive microsensor used for the measurement of the dielectric constant ε_r is composed of a combination of CMOS-compatible materials (see Fig. 2): A thin metallic interdigitated electrode structure (IDS) fabricated on a dielectric substrate is coated by an ultra thin dielectric layer for resistance to the environment and for electrical insulation.

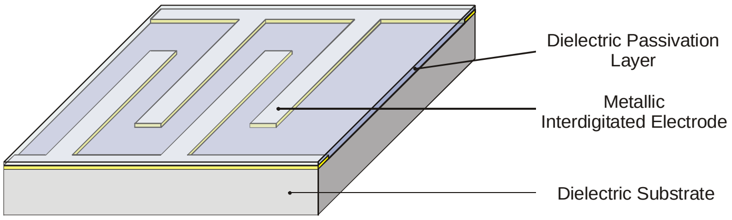


Fig. 2. Detailed view of the microsensor

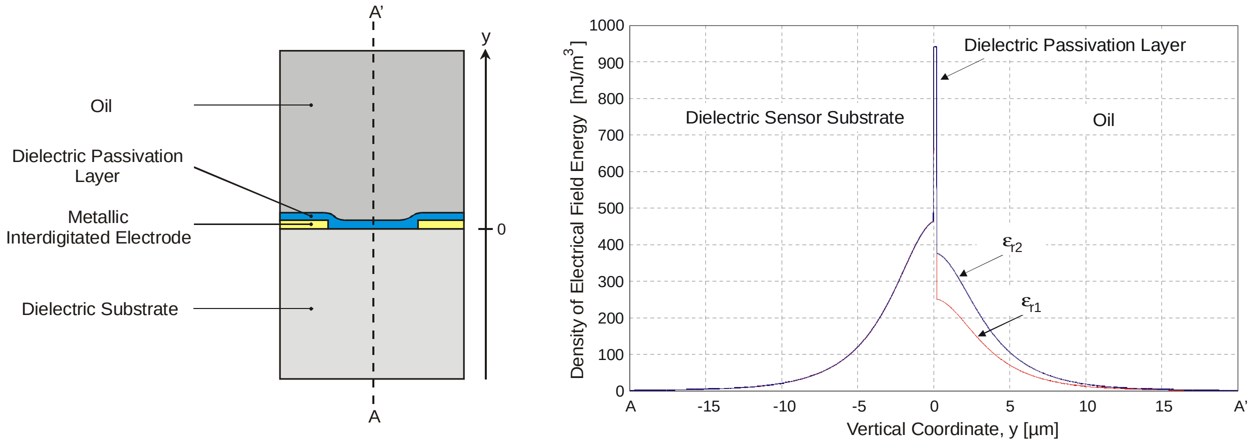
3.2 Modeling aspects

For evaluation of the influences of the geometrical sensor parameters numerical simulations based on a 2-dimensional model of a unity cell of the IDS were done (see Fig. 3a). Thereby, the optimization was focused on the sensitivity and the sensor capacitance without oil loading, herein after referred to as “offset capacitance”. The formulation of the optimal sensor design was distinguished by the following primary aspects:

- maximization of sensitivity or relative capacitive swing due to changes in oil permittivity, resp.
- matching of sensor capacitance and working range of signal pre-processing circuit
- adaptation of sensor total geometry to a surface mountable package with the JEDEC SOIC-8 outline

The sensitivity is the most important parameter and was optimized through the simulation of the penetration depth of the electrical field into oil over a broad range of design variations and material combinations (see also Fig. 3b). In consideration of listed requirements the following sensor geometry was finally chosen:

electrode width:	10 µm
electrode spacing:	8 µm
overall dimensions of IDS:	2.1 mm x 1.5 mm



(a) (b)

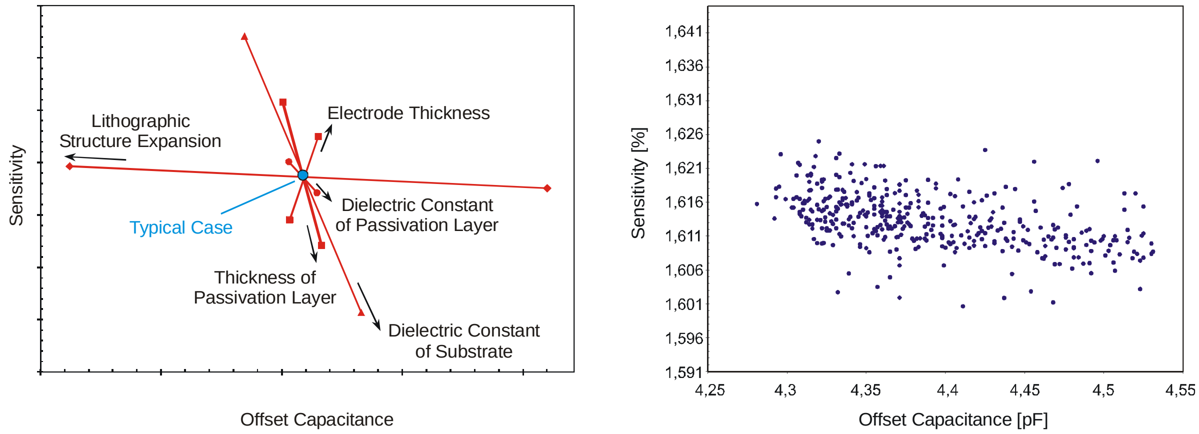
Fig. 3. Simulated changes in density of electrical field energy along path A-A’ due to different dielectric constants of oils (applied dielectric constants in (b): ε_r(substrate) = 3.75; ε_r(passivation layer) = 7.5; ε_r(oil 1) = 2.0; ε_r(oil 2) = 3.0)

3.3 Fabrication

The interdigitated electrodes were fabricated by rf sputter deposition of a tungsten titanium alloy (90 % W, 10 % Ti) onto amorphous quartz glass. After photolithography the finger structures were patterned by a special reactive ion etching process using a CF_4/O_2 gas mixture and coated by a thin silicon nitride film (SiN) in a low pressure chemical vapour deposition process (LPCVD). Afterwards for bondpad creation the SiN layer was locally opened by dry etching using a photoresist mask. Next aluminium was deposited and structured by wet etching.

After electrical tests at the wafer level the individual microchip was mounted onto a standard lead-frame with a JEDEC SOIC-8 outline. It was then encapsulated by a special plastic, open-cavity moulding technique, patented by Eurasem B.V. [3], whereas the sensitive electrode structure was protected against particle contamination during moulding. This package concept ensures a high resistance to the environment and is suitable for automotive temperature ranges and durability.

In the context of process total tolerance analysis, the technological variations of all single process steps were investigated regarding their relevance and weighting for sensitivity deviation and offset capacitance (see Fig. 4a). (For further consideration, the sensitivity was defined by the relative capacitive swing from ε_r = 2.0 to 2.1.) Due to selective optimization and observations of individual fabrication steps this work was designed to realize a calibration free, highly accurate structure.



(a)

(b)

Fig. 4. Influence and significance of process tolerances on offset capacitance and sensitivity
(a) - Simulated total tolerance analysis; (b) – Measured offset capacitances and sensitivities

As shown in Fig. 4a the lithographic structure expansion represents the most significant influence regarding deviation of the offset capacitance. By changing the ratio between width and spacing of the interdigitated electrodes the highest capacitive variation is induced while the sensitivity is still barely affected. In reference to this, a special attention is turned to the permittivity of the quartz substrate. This parameter must be monitored by either the material supplier or by in-coming inspection controls at the chip manufacturer’s site using well-known permittivity characterization methods, e.g. by the so-called two fluid method [4].

After measurement of the offset capacitance of air (ε_r = 1.00054, 20 °C, [3]) each single sensor element is loaded with a small amount of cyclohexan (p.a.) for sensitivity testing. This volatile unpolar fluid was chosen concerning its permittivity of ε_r = 2.024 at 20 °C [5], which is electrically comparable to oil in the range of ε_r = 2…6. As depicted in Fig. 3 the measured deviation of sensitivity and offset capacitance fits well to the simulation results.

The final packaging and moulding procedure did not lead to a measurable increase in deviation of sensitivity (see Fig. 4) because the covering of the sensitive area by mould compound particles was smaller then 1 %. While before packaging an overall sensitivity variation of 0.77 % - based on average - was detected, this value was 0.76 % after packaging. The small decrease of mean sensitivity from 1.63 % to 1.61 % , shown in Fig. 5, is directly related to parasitics caused by the capacitance of the interconnections inside the package.

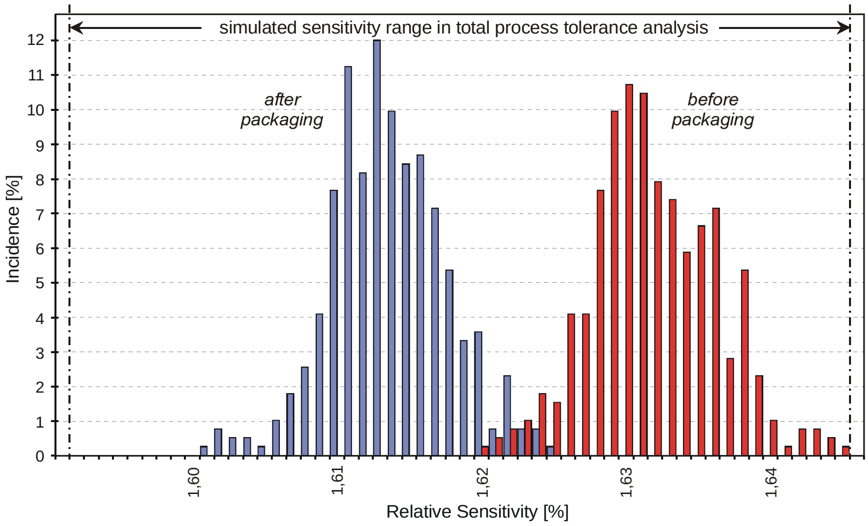


Fig. 5. Bar charts of relative sensitivity in comparison to simulated range of total process tolerance analysis

A reduction in the deviation of offset capacitance could be achieved by further process optimization at the manufacturing site or by transition to integrated solutions at a system level, e.g. by a hybrid integration of sensor chip and signal processing circuit in a single multi-chip module (MCM).

4 Measurement Results

The measurement of impedance over a given range of frequency, the so called impedance spectroscopy, allows for the characterization of dielectric materials and creates a variation to the classification of the dipoles in this material.

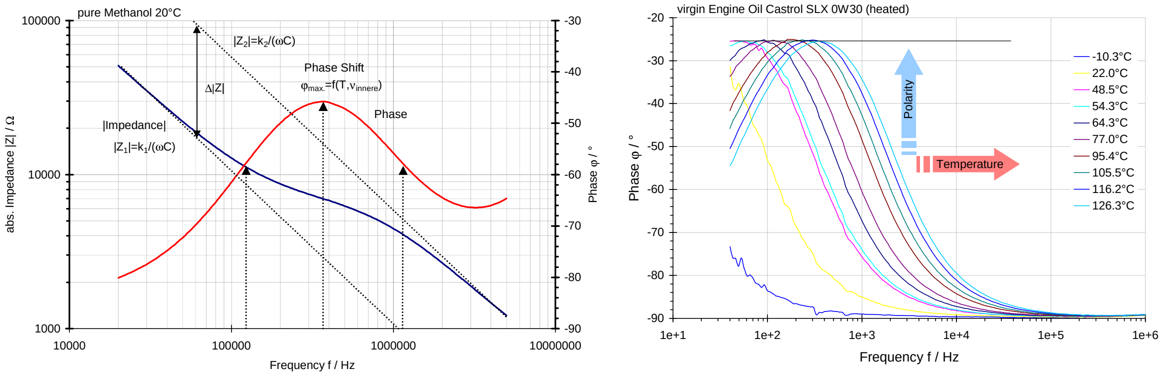


Fig. 6: Impedance spectra of methanol (a); Temperature dependency of phase shift (b)

Figure 6a shows the absolute value of impedance $|Z|$ and the phase measured with methanol (20 °C). The phase curve shows a maximum at a certain frequency $f_{\max}$. For liquids of higher viscosities, e.g. engine oil we found the phase maximum at lower frequencies. Furthermore, the frequency at phase maximum depends on the temperature which can be seen in Fig. 6b. Apart from the temperature dependency Fig. 7a shows the dependency of the phase on the petrol dilution in oil. By increasing the content of petrol the phase decreases to lower values at a certain frequency. However, it has a beneficial effect to determine the frequency at a certain phase ($\varphi = 60°$) with the secondary condition $|Z|$ = min. The previous results lead to the assumption that the resonant frequency depends on the viscosity. By determining the frequency at a phase of $\varphi = 60°$ we found a dependency on the content of petrol which is shown in Fig. 7b. When comparing this data with the viscosity values, a connection between the viscosity and the frequency becomes very obvious in Fig. 7b. As it becomes apparent, among other things also from [6], the impedance spectroscopy is a suitable method, in order to determine the change of oil viscosity. The frequency at maximum phase can be interpreted as the resonant oscillation of the existing dipole collective in the dielectric material.

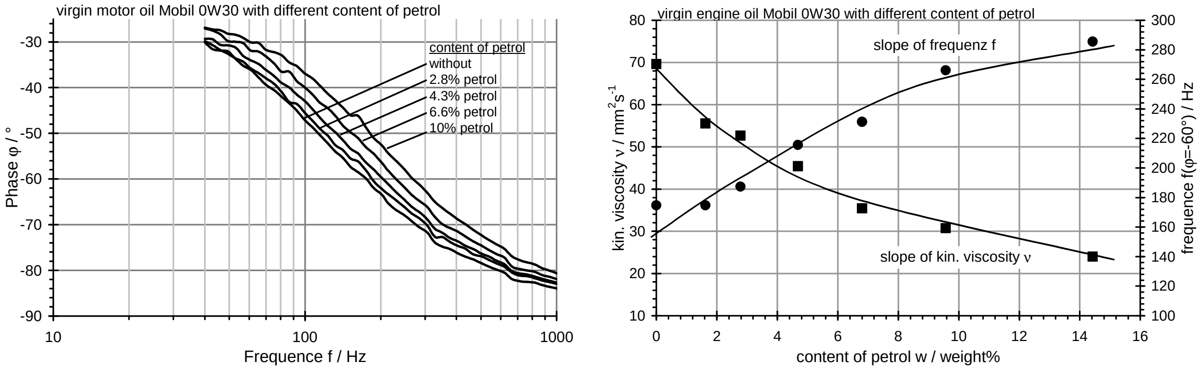


Fig. 7. Phase shift dependency from petrol dilution (a); Kinetic viscosity vs. content of petrol and frequency at $\varphi = 60°$ vs. petrol dilution (b)

5 Conclusions and outlook

A highly reliable microsensor has been developed. The packaging concept allows easy sensor integration at the board level as an SMT component. This microsystem will be a stand-alone working oil condition sensor providing permittivity and viscosity measurements and is capable of being integrated into various designs of automotive oil sensors. The main objective of this work is the successful integration of an oil condition monitoring system into an existing oil level sensor (Fig. 1a). The result is an upgraded automotive sensor without the requirement for a new mechanical interface to the oil pan.

References

[1] W. Warnecke et al., *Belastungsgerechte Ölwartung mit ASSYST*, MTZ Motortechnische Zeitschrift 59 (1998) 7/8, pp. 414-421

[2] B. Jacoby et al., *A Multifunctional Oil Condition Sensor*, AMAA 2001 Yearbook, pp. 157ff

[3] I. Van Dommelen, Plastic Packaging for Various Sensor Applications in the Automotive Industry, AMAA 2002 Yearbook, pp. 289-296.

[4] The Institute for Interconnecting and Packaging Electronic Circuits, Permittivity (Dielectric Constant) and Loss Tangent(Dissipation Factor) of Materials (Two Fluid Cell Method), IPC-TM-650 Test Methods Manual, 1987.

[5] D. R. Lide (Ed.), CRC Handbook of Chemistry and Physics, 81rd Edition, 2000-2001.

[6] Hellwig, Guenther; Normann, Norbert; UhL, Guenther "A sensor on dielectric basis for the on-line characterization of engine oils (Alkalinity, Viscosity)"