Calculations on Micromachined Electro-Thermal Sensor Devices

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Summary:

In this contribution the experiences gained using ANSYS/Multiphysics software for analysis of micro machined electro-thermal sensor devices are described.

The sensor construction is required to fit into a given set of requirements, which are of electrical, thermal, mechanical and geometric nature.
A series of coupled simulations (electro-thermal ~, mechanical ~, modal analysis ~) allows, in theory, the analysis and characterisation of the device. However to achieve reasonable results the design engineer has to face some limitations of the current software release. It is required to set up the fem model as well as the constraints very carefully. Therefore heat transfer and contact resistance are treated with special interest in this paper.

Keywords:
MEMS, ANSYS/Multiphysics, electro-thermal, sensor

1 Hot Wire Sensors

Today *hot wire sensors* are common devices in total pressure (vacuum) measurement. They are usually based on the Pirani principle: at very low-pressure levels the heat transfer rate is strongly dependent on the pressure itself.
The wire is heated electrically. Small pressure variations result in totally different cooling effects. Since the resistance of a wire changes with its temperature a simple electrical set up allows either a voltage or current signal output signal.
Application of micro technology on those classic devices is advantageous because cheap mass production and higher performance are enabled.

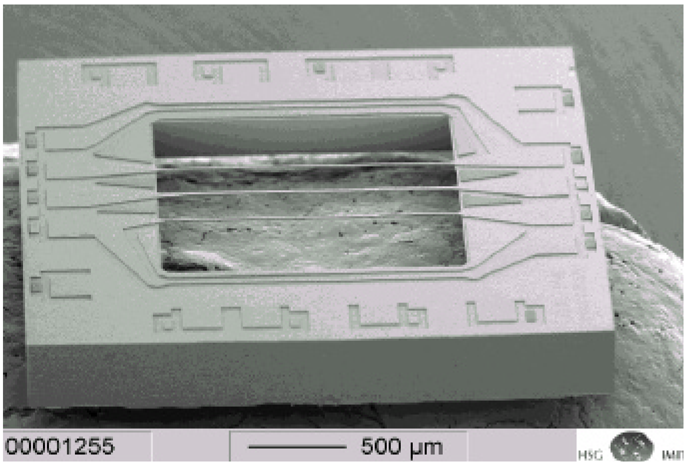

Fig. 1:
SEM micrograph of a micromachined inclinometer chip

Further, a totally new class of devices is opened up by the same technology: *Micro Inclinometers*.

With a new design, presented here, small rotations (angle) can be measured by a micromachined thermal sensor device.
At ambient pressure free convection occurs as a function of the heated wires' temperature. The heat is transferred not only just upwards by the convection but to sensing wires, placed in the lateral neighbourhood, too. These new devices turned out to be highly sensitive towards rotational movement around the wires' axes. One of their major advantages is, that except the surrounding gas, no movable parts are required any more. Reliability and cost therefore perform much better compared to standard inertial systems.

HSG-IMIT is developing micro machined inclinometers for industrial applications. Figure 1 shows the SEM micrograph of an early prototype inclinometer chip. This chip is made out of silicon and manufactured by advanced deep etching processes.
A cross section of a test set up is given by the sketch (Figure 2) at the right.

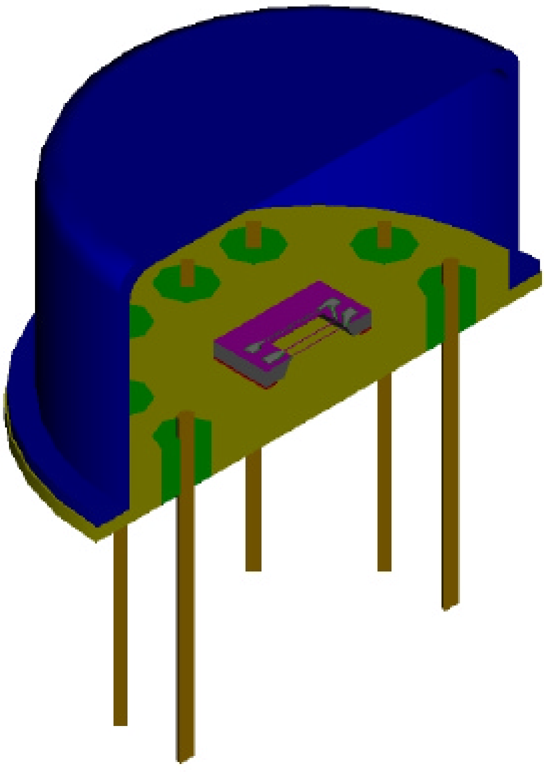

Fig. 2:
Sketch of thermal inclinometer sensor set up

2 Simulations

One, of a number of tasks, in thermal sensor design is prediction of electro-thermal-mechanical behaviour of the heated structure; the hot wire in our case.

At a first glance ANSYS 5.6 seems to be suitable for this task, since

- 3D electro-thermal elements are available and
- transfer of calculated nodal-temperatures to mechanical computation is feasible.

In a first approach we used the ANSYS Solid69 element for electro-thermal calculation. Figure 3 shows the FEA model of the hot-wire. The wire consists of pure crystalline silicon (cyan). Electrical connectors are realised by a structured aluminium layer (blue-magenta).
Electrical as well as thermal conduction is calculated simultaneously by ANSYS. Suitable boundary conditions at the cross-section of the wire have to be applied by the user. We found that applied voltages for the electrical quantities and heat-transfer rates for thermal quantities ended in reasonable results.

The very important cooling effect of free convection around the wire is taken into account by some preliminary analytical calculations. Hand calculations of free convection are available for standard cross sections (e.g. for cylindrical wires) [1]. Running through computation of Grashof ~, Prandtl ~ and Nußelt numbers allow that a heat transfer rate, which is a function of local temperature, can be found for reliable ANSYS simulations.

Figure 4 shows the analysis results: temperature distribution on the electrically powered hot wires' surfaces.
Beside this the mean over temperature, as a major characteristic sensor parameter, is computed by integration over the structure.

Figure 5 shows a typical result of an optical measurement of the thermal sensor in action. Some of the post processing features know from ANSYS (like *path plots*) can be used in the measurement system as well.

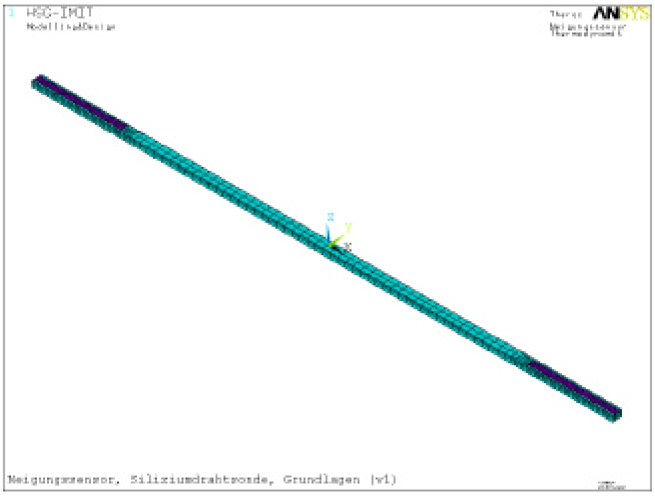

Fig. 3: Hot Wire FEA model with

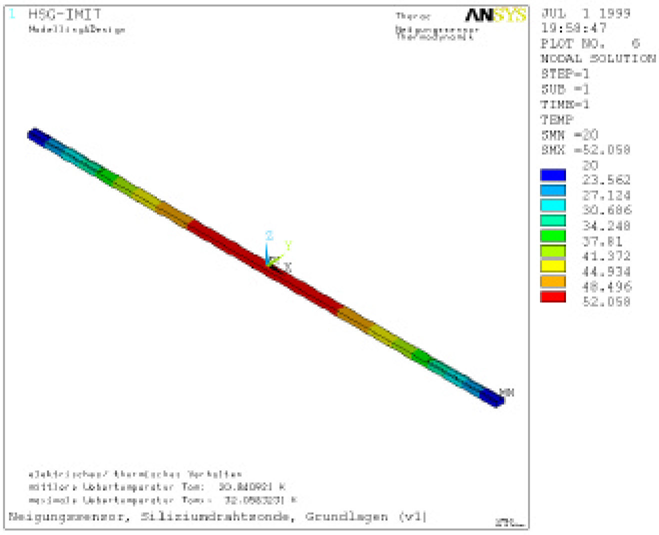

Fig. 4: Temperature distribution on powered hot wire

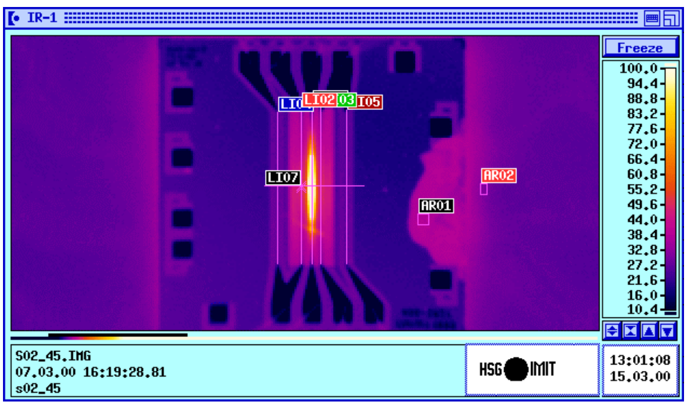

Fig. 5: Measurement of temperature distribution on the powered sensor device

While calibrating our FEA models we experience that either local temperature can be tuned to fit into the measurements or the total power, but not both at the same time.
This model failure occurred since we neglected the contact resistance between the aluminium layer and the silicon wire.

After the electro-thermal calculations a mechanical analysis was added to determine:

- the stress in the structure and
- deflection due to the buckling of the bimorph.

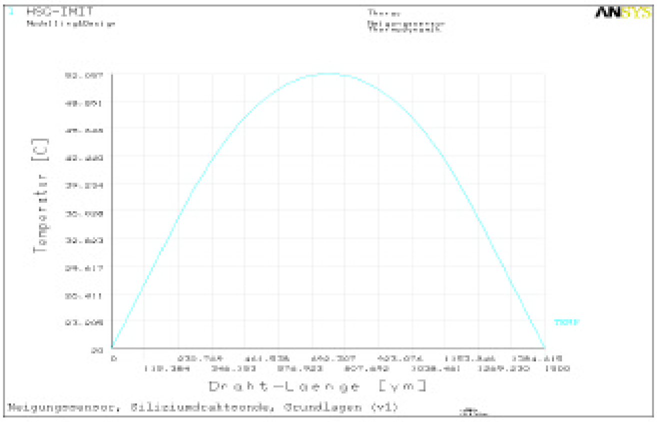

Fig. 6: Temperature distribution along powered hot wire

Of special interest are the out of plane deflection (see Figure 7) and the stress state in the aluminium-silicon interface.
Usually a high over-temperature level is desired together with a more or less uniform distribution along the wire.
These objectives are often not feasible because of the stress and deflection status of the structure.

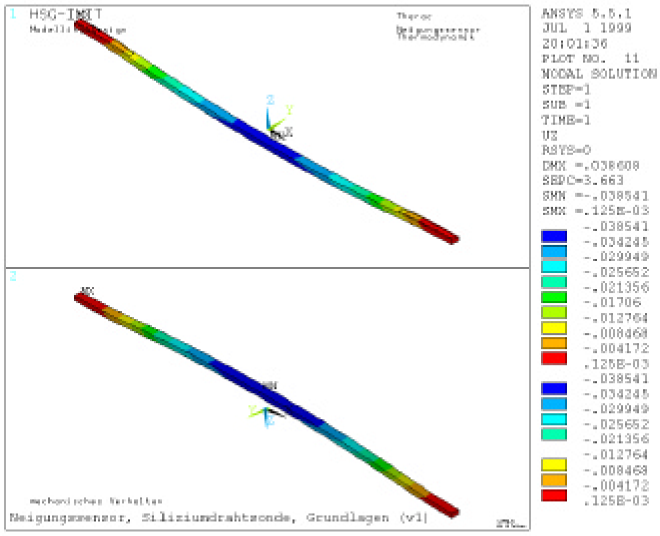

Fig. 7: Deflection of hot wire due to over-temperature

Since the thermal expansion of silicon is different from that of aluminium, the wire is loaded by an internal moment if over-temperature is present. The out of plane deflection is a higher order bias effect since heat transfer to the sensing elements in the neighbourhood varies with the change of the wires' position. Figure 7 show the z-deflection of the wire due to the over-temperature calculated in a previous analysis step.

Further, high shear stress in the silicon-aluminium interface may lead to an undesired detaching of the aluminium layer. Therefore the stress level in these interfaces has to be checked very carefully while increasing the over-temperature. Figure 8 illustrates the distribution of the principle stress S1 that represents the maximum tension that is present in the silicon wire.
Figure 9 however gives an idea about the shear stress in the interface plane, perpendicular to the wires' direction, which strains the aluminium layer.

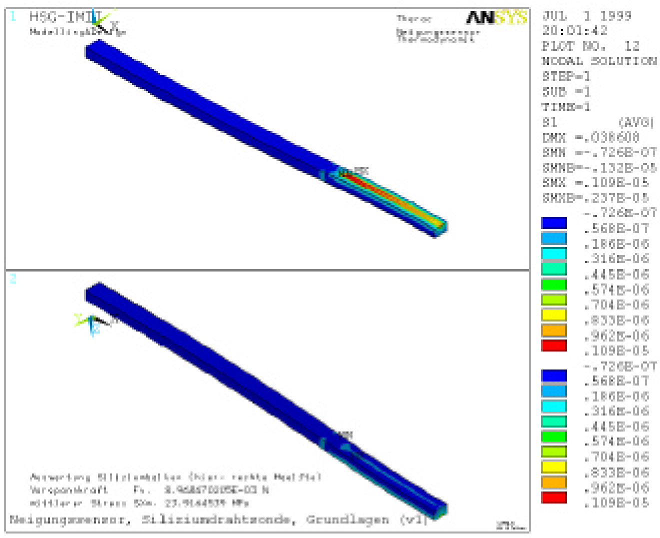

Fig. 8: Principle stress S1 in silicon wire

3 Conclusions

ANSYS allows the efficient modeling of hot wire sensors including the major physical effects.
The authors used the solid69 element for the prediction of the electro-thermal behavior and added a mechanical computation, loaded with the temperatures calculated in the first step. All major sensor parameters could be calculated, at least theoretically.
Unfortunately the effect of contact resistance could not be included, since a tiny intermediate layer of elements with suitable, adapted conduction is needed in ANSYS to represent this effect.
The authors had to handle a structure with a high aspect ration (long wire, with small cross section) that contains in addition a thin layer on top of its' surface. Usually some effort is needed to mesh such geometries. Now in a further step a thin (bad aspect ration) layer has to be applied to consider the contact resistance. This was no more possible with respect to cost and standard hardware resources.

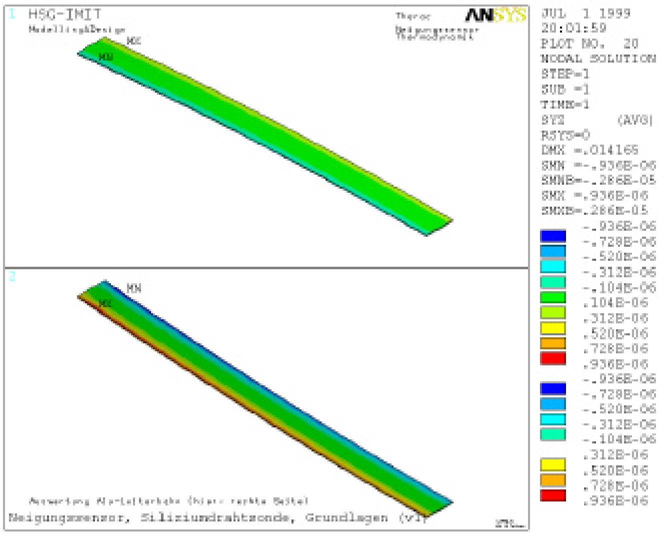

Fig. 8: Interface silicon – aluminum:
Shear stress (in plane) in aluminum layer,
perpendicular to wire orientation

Since ANSYS states to be suitable for MEMS the authors would like to suggest some enhancements for future ANSYS releases:

- Implementation of an electro-thermal contact-resistance 3D area-element.
- Automated heat transfer rate for "simple" standard structures

ANSYS for MEMS still offers interesting challenges.

4 Acknowledgments

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5 References

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[2] Förderung von Verbundforschungsprojekten im Rahmen der "Zukunftsoffensive Junge Generation" des Wirtschaftministerium Baden-Württemberg vom 31.10.1997, Az: 4-4331.1/56 (Staatsanzeiger Nr. 44/1997).