Function Scale Integration – Embedding Sensors in Materials for Structural Health Monitoring

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ABSTRACT

Embedding sensors for structural health monitoring (SHM) confronts us with two opposing challenges: First, we want reliable data with high spatial resolution from the inside of a material. Second, a sensor is a foreign object, a "wound" in the material which may downgrade its properties. This paper discusses ideas to integrate sensors in material without changing its macroscopic performance to the worse.

First, the paper describes the impact of miniaturization on sensors. It is our idea to reduce the volume of the sensor to the minimum which is needed to guarantee the function. This approach is called **function scale integration**. The impact of size on sensitivity and noise is discussed at the example of an acceleration sensor.

Finally, the paper describes a new thin and flexible foil sensor which can monitor the process of polymerization of a compound material. This sensor is a first step in the direction of function scale integration. Possible further development is discussed.

INTRODUCTION

For structural health monitoring of a system, sensorial data from its material is needed. Therefore, embedding sensors in material is a core challenge of SHM. The Integration of a sensor always means two tasks: First, realizing sensing structure which will generate the desired data. Second, realizing a path of communication from this elementary sensor to the place, where you perform the evaluation and decide about consequences. Using the methods of micromachining, i.e. thin film technology, lithography and etching, we can make small elementary sensors or sensor chips, the order of magnitude is a millimeter. Nevertheless, an impurity of 1 mm size in a material is a foreign body which may change the macroscopic behavior. It might be the origin of fatigue cracks in metals or of delamination in compound materials. It is necessary to avoid these negative impacts, so that we can define our task of sensor deployment in the following way:

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Embedding sensors in a way which does provide the information you need for monitoring but which does not downgrade the macroscopic behavior of the material.

In a way, the sensor and its interconnections may be considered as a wound in the material. The idea of this paper is to discuss, what technologists may do to minimize this wound and its possibly destructive effects.

HOW TO INTEGRATE SENSORS

Asking from a very general position how sensor integration in a technical item may be performed, we find four possible strategies. As an example, the item might be a cog wheel in a gear-box. There are no sensors in cog wheels today, but there are strong reasons to think about "sensorized" cogs.

1. We can realize sensor elements in a microtechnology process line and embed them on the surface or inside of the material [1, 2]. This hybrid integration approach is the usual way to embed sensors in macroscopic systems.
2. We may integrate the preparation and structuring of sensor films and interconnections in the process flow used to prepare the item. In our example, the process of surface polishing and covering with a tribological hard film might be complemented with process steps to deposit conducting and insulating films in order to embed strain gauges in the surface.
3. We may make use of intrinsic properties of the material. They might be naturally there or deliberately generated. An example would be to determine the temperature of a metal measuring its magnetic properties.
4. Finally, we might think of growing sensor elements during the material generation using a kind of advanced self assembly. This is the way sensor cells in natural systems grow. On the molecular level, first approaches in this direction are investigated. To grow a sensor element, we would have to know how to make a technical equivalent to a living cell. Up to now, there is no concept how this might be done, so this approach will not become reality in near future.

In this paper we focus on the first path, making sensors separately and integrating them in a hybrid way.

HOW SMALL CAN A SENSOR BE?

Lessons learned from nature

In Figure 1 we compare two different systems for pressure sensing. The picture at the right (D) shows a natural sensor, a Meissner corpuscle from the foot of a rat, which has a size of about 50 µm. Meissner corpuscles are mechanoreceptors situated between the outer skin (Epidermis) and the inner skin (Dermis), in a human fingertip there are about 10-50 Meissner corpuscles per mm². The sensor is a fluid-filled ball which contains the sensorial nerve terminal [3]. It is rapidly adapting, this means that it corresponds mainly to the change of pressure on the skin with a maximum sensitivity at 50 Hz. The skin has several mechanical receptors for static, slow and fast changing pressure signals.

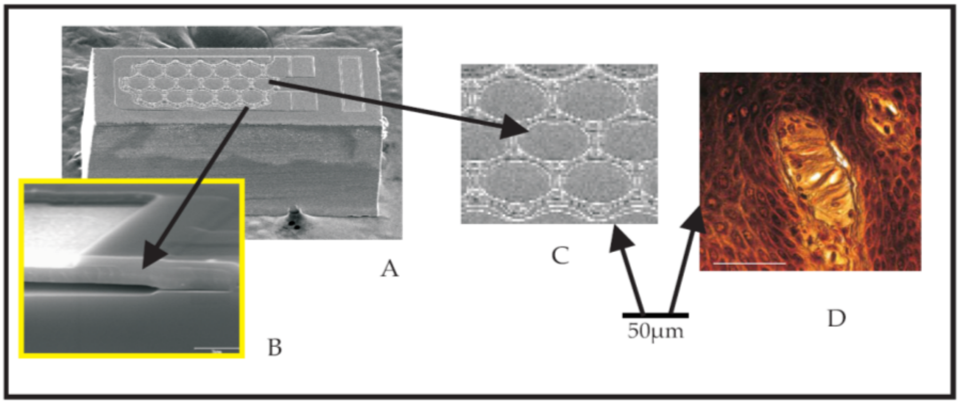

Figure 1: Comparing a small micromachined pressure sensor to its natural counterpart: A: A capacitive pressure sensor made by surface micromachining using a thin film of polycrystalline silicon [4]. B,C: Details. D: Mechanoreceptor from the skin of a rat (Meissner corpuscle) seen with an optical microscope (Figure by U. Dicke, Univ. of Bremen) [5]. Figure C and D are on the same scale: a single silicon sensor membrane and the Meissner corpuscle are both of approximately 50 µm diameter.

The left picture shows the smallest pressure sensor from the IMSAS cleanroom [4], it has a chip size of about 600 µm (A). The sensor is made by surface micromachining technology. It has 16 membranes made of a polycrystalline silicon thin film with a small cavity below each membrane. The membrane and the substrate act as the two plates of a capacitor, as you can see in picture B. When the membrane is pressed down by increasing pressure, the capacity is going to rise. In the center of the figure (C) we plot a blow up of sensor membranes on the silicon chip. The membrane is the part which effectively performs the sensor action. It has a size comparable to the Meissner corpuscule, while the whole sensor chip is much larger. Looking closer we find that the sensor function is realized within some thin films on top of the surface of the substrate (hence the term of surface micromachining) within a volume of $5\cdot10^{-4}$ mm³. This compares to the volume of a Meissner corpuscle, which is $2\cdot10^{-4}$ mm³. The volume of the chip shown in Figure 1 (A) is 0.1 mm³. We find that only 0.5% of the volume are actually “working”. The rest is some ballast which stems from the production process in silicon wafer technology but does not contribute to function. Using function scale integration, we will take off the ballast and reduce the sensor to those elements which are relevant for the function. In this way, the sensor function is realized in a thin flexible membrane of about 10 µm which can be embedded in material. We call this approach function scale integration [5]. In 1990, the technological realization of such a structure would have been quite hopeless. However, silicon technology has made rapid progress concerning thin chip technology. The driving force is RFID-technology. The identification chip in a RFID tag is a silicon chip which is 10 µm thick and quite flexible. First examples of sensors made on flexible thin foils have been demonstrated, e.g. a thermal flow sensor on a 10 µm polyimide membrane [6]. We expect a number of sensor devices realized as thin membranes within the next years. Obviously, to allow function scale integration, the sensors must not just become thin, but also the sensor area has to be reduced.

The impact of miniaturization at the instance of an accelerometer

At this point we arrive at a crucial question: what is the impact of extreme sensor miniaturization on the sensor function? Certainly, there will be technological problems, but is there a fundamental limit due to basic laws of physics? For many transduction principles the sensor signal will be proportional to the surface (pressure, force, humidity, chemical or optical sensing) or to the mass (inertial sensing). The analysis of the impact of miniaturization on signal and noise ratio must be done for every transduction principle separately. However, to demonstrate the general approach of the argument, we will show it by one example. This example is the accelerometer, because for this sensor sensitivity and noise can be estimated from basic principles.

A micro-machined accelerometer is shown in figure 2. It is a spring-mass system with resonance frequency ω_0 and quality factor Ω. A seismic body made of a thin plate of polycrystalline silicon is held by silicon springs. Under acceleration a, the mass is deflected for a small δx, some fractions of a micrometer. This small deflection is measured using comb-structures which act as differential capacities. The resonance frequency is given by the mass m and the spring constant D:

$$\omega_0 = \sqrt{\frac{D}{m}} \qquad D = \frac{ma}{\delta x} \ . \tag{1}$$

Generally, the application will dictate the resonance frequency (e.g. a minimum of 10 kHz for automotive applications). For the quasistatic regime, when the frequency is small with respect to the resonance frequency, the resolvable acceleration a_{min} can be calculated from equation (1) as

$$a_{\min} = \delta x_{\min} \omega_0^2 \ . \tag{2}$$

It only depends on the resonance frequency and the minimum detectable deflection δx_{min}, not on the mass. If we increase the mass we have to increase the spring constant to keep the resonance frequency and thus larger mass does not help to improve resolution. On the other hand, if the system is smaller, etching technology will allow finer inter-digital capacitive sensors, δx_{min} will be smaller and resolution becomes better. The consequence is, against first intuition: a good accelerometer has a small mass and a very precise displacement measurement. For this reason, technologists make the seismic mass out of a thin film, which may be etched very precisely using the DRIE (Deep Reactive Ion Etching) process. When we have a look at an accelerometer (figure 2) we find an extremely small mass around 1.5 µg. A grain of rice for example weighs around 7000 µg.

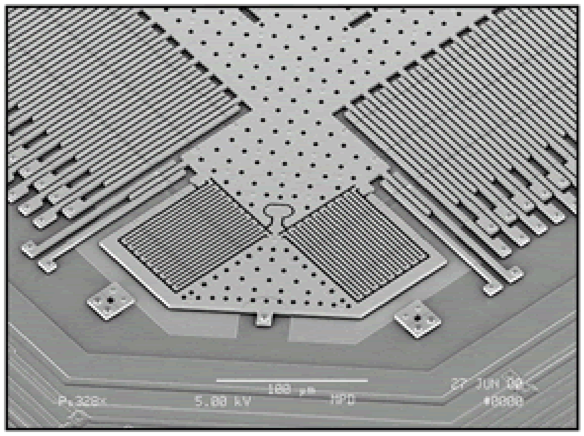

Figure 2: A commercial accelerometer, seen by SEM. The seismic mass is made by a thin film of polycrystalline silicon. The displacement is measured using differential capacities realized by inter-digital electrodes. Figure by Analog Devices (www.analog.com).

The principal aim in sensing is not signal strength, but the ratio of signal and noise. The small inertial mass is subject to thermal noise which generates a small chaotic movement, such as the chaotic shivering of the smoke particles in the famous experiment of Brownian motion. In one dimension, the energy stored in this movement will be $E = 1/2\,kT$ with the Boltzmann constant k and the temperature T. For the case of the accelerometer this results a noise equivalent acceleration a_N of

$$a_N = \sqrt{4kT\frac{\omega_0}{mQ}df} \quad [7]. \qquad (3)$$

df is the measurement bandwidth. When the mass m is reduced, noise rises. For the accelerometer shown in figure 2, the small mass of 1.5 µg results in a noise equivalent acceleration of 5 mg, this is 1/200 of the acceleration of gravity. Thus, we find that in the case of the accelerometer, miniaturization rather improves than reduces sensitivity, but increases noise. The tradeoff of those two impact factors has an optimum at a very small mass.

AN EXAMPLE: EMBEDDING SENSORS IN CARBON FIBRE COMPOUNDS

As an example of current work on function scale integration, we want to discuss the integration of sensors in Carbon Fiber Reinforced Polymers (CFRP) laminates [8]. A challenging task is to monitor the polymerization process of this material. Polymerization affects the mobility of the molecules in the material and thus the dielectric coefficient ε [9, 10]. This can be measured using a surface capacitor made by comb electrodes on a substrate. Comb structures on electronic flexboard materials are available for polymerization experiments. A laminate is processed around the sensor and from the change of the dielectric function over time information about the polymerization process is gained, which is a valuable tool for experimental process analysis. Once the polymerization is complete, the sensor cannot be removed any more. It is not possible to predict the long term impact of the foreign body in the

CFRP. It is known that millimeter-sized embedded sensors can be a source of delamination in composites [11, 12, 13]. On the other hand, Satori [14] has embedded 50 µm-diameter fibers in a laminate and did not observe weakening. Thus this type of sensor has a drawback for the monitoring within the production of airplanes parts and other security sensitive components made of CFRP. To use a sensor in real production and then leave it, a new generation of sensors is needed. They must be small and very flexible in order not to downgrade the macroscopic mechanical stability, as we stated in the introduction. A structure which resembles the carbon fibers in size and attitude would be most appropriate. To reach this aim, we have developed a new sensor generation as shown in figure 3. The sensor is made of two layers of polyimide with a metal layer embedded in the center [15].

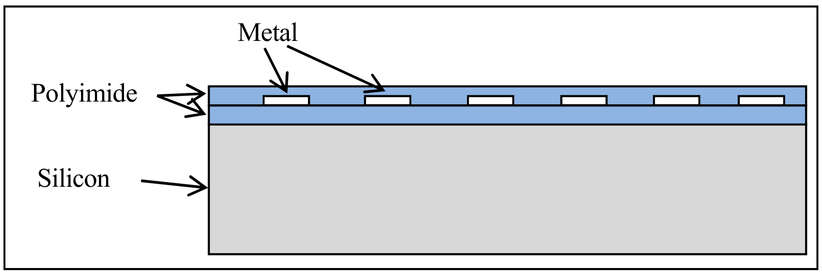

Figure 3: A dielectric sensor made by use of polyimide technology. A polyimide film is prepared on a silicon wafer. Next, the metal is deposited and structured. Additionally, a second polyimide layer is deposited and structured. Finally, the polymer – metal – polymer sandwich is removed from the silicon substrate.

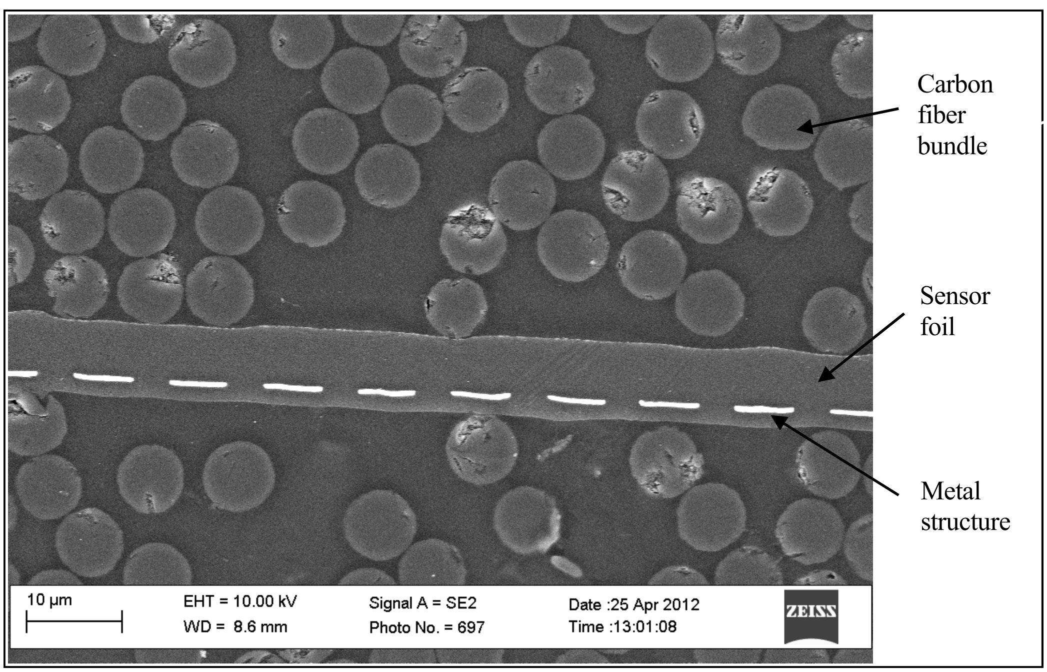

Figure 4: SEM picture of a thin sensor for the measurement of local dielectric function embedded in a carbon fiber compound (CFRP). The carbon fiber bundles have diameters of about 8 µm. The sensor foil is 10 µm thick. Within the sensor foil the metal structures appear as a broken white line.

In figure 4, a polished cross section of the laminate with an embedded sensor is shown. The sensor is about 10 µm thick and the carbon fiber bundles have diameters of around 8 µm. By having the flexibility of a foil, the sensor can adapt to the geometry of the laminate material and follow elastic deformations. Although, being a foil of about 3 x 3 mm² area, the sensor is a disruption of the polymer – carbon fiber matrix. Thus, to achieve the aim of integration without wounding the matrix we have to proceed further. A future step will be the transit from a membrane structure to a net structure allowing polymer bridges through the holes as sketched in figure 5. Single fibers, each of them made of a polymer – metal sandwich, are spread out in the material for capacitive sensing.

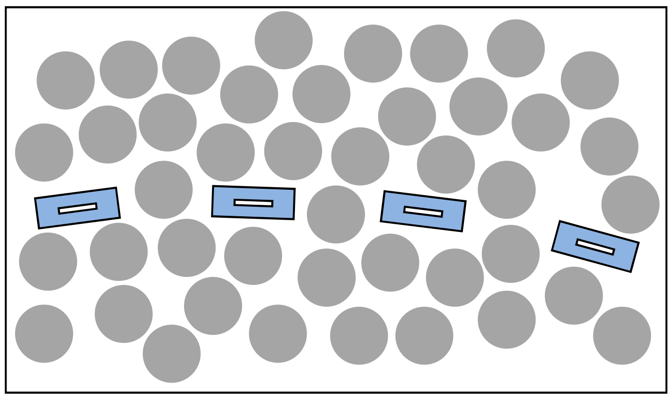

Figure 5: Idea of a future sensor for the dielectric function of the CFRP. The sensor is reduced to a net of single fibers which adapt to the carbon fiber structure. This sensor net permits a minimum impact of the sensor to the structure.

OUTLOOK

For future structural health monitoring we will have to develop sensor systems which will take effect more like natural parts of the material than like foreign bodies. This aim needs to find new ways of sensor technology and integration techniques. Sensors made in thin foils instead of thick silicon chips outline a first step in this direction. Sensor scientists are faced with a number of fascinating challenges:

- realizing small and thin sensors
- to step further from sensor foils to sensor nets
- accomplishing small and flexible electronic circuits for local data processing
- developing new integration and interconnection methods
- finding simple but powerful control algorithms which can be realized locally

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