Subproject B2: “Experimental characterisation, modell adaption and reliability: Micromechanical electrostatic field sensor for the detection of remanent charges”

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Electrostatic driving and capacitive read out play an important role in MEMS. These systems consist of the micromechanical component and the driving and the detection electrodes, respectivally. The electrodes are placed on insulating materials and in some cases they are coated with an insulating layer to prevent short circuit. It has often been observed that insulating materials carry charges for a long time after charging. The effect of these charges will be shown on the example of a silicon cantilever actuator (Figure 1). It consists of four silicon cantilevers which are independently controlled by four aluminum electrodes. To increase the electric field strength and prevent a short circuit the electrodes are coated with a dielectric layer (SiO_2) or layer stack (Si_3N_4-SiO_2-Si_3N_4).

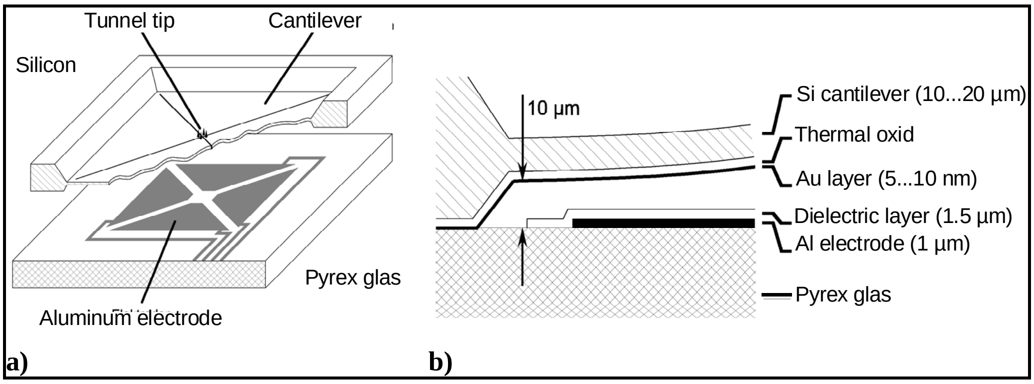

Figure 1: Silicon cantilever actuator with a dielectric layer on the driving electrode [1]
a) exploded view, b) cross-sectional view

Figure 2 shows the static deflection of one cantilever tip vs. the applied voltage [1]. At high voltages electric gas breakdown in the air gap occures and the cantilever shows caotic fluctuations. Decreasing the applied voltage reveals a strong shift of the hole characteristic curve along the x-axis and causes electrical gas breakdown at sufficiently high negative voltages. This phenomenon can be explaned by the discharge process. During this event an avalanche of free electrons and ions is generated in the air gap between the cantilever and the driving electrode. They traverse the gap and are stopped and neutralized by charge exchange at the surface of the dielectric layer coating the electrode. Consequently, the electrostatic field is reduced locally and the discharge is terminated so that the force drops and the deflection of the cantilever tip decreases. The deposited surface charges effect the micromechanical system as an additional offset voltage as can be seen from the shift of the characteristic curve in Figure 2.

To visualize the qualitative charge distribution on dielectric layer on top of the driving electrodes the cantilevers were removed and a picture was taken using the scanning electron microskop (SEM). Because the yield of the secondary electrons depends on the electrical surface potential the charged areas in Figure 3 become more light in case of negative charges and more dark in case of positive charges in relation to the not charged areas. To avoid an influence on the charges the electron beam parameters have to be chosen very carefully [2].

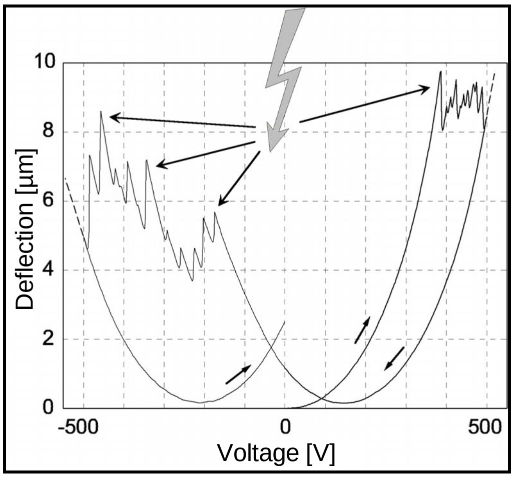

Figure 2: Static deflection of the cantilever tip vs. the applied voltage [1]

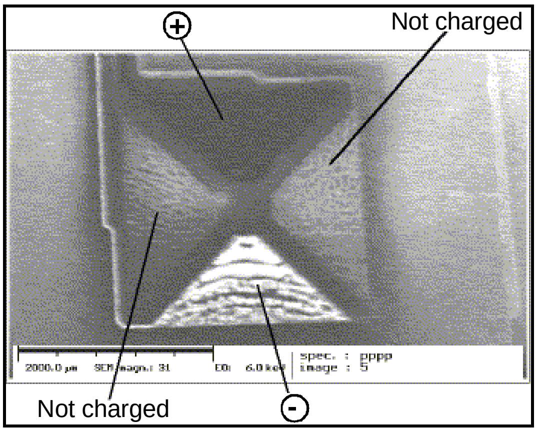

Figure 3: SEM-view of the driving electrodes after electrical breakdown in the air gap, the cantilevers are removed [1]

Techniques to measure the charge distribution are the Kelvin probe force microscopy (KPFM) [3], the electric scanning force microscopy (ESFM) [2], [3] and the electrostatic voltmeter[2].

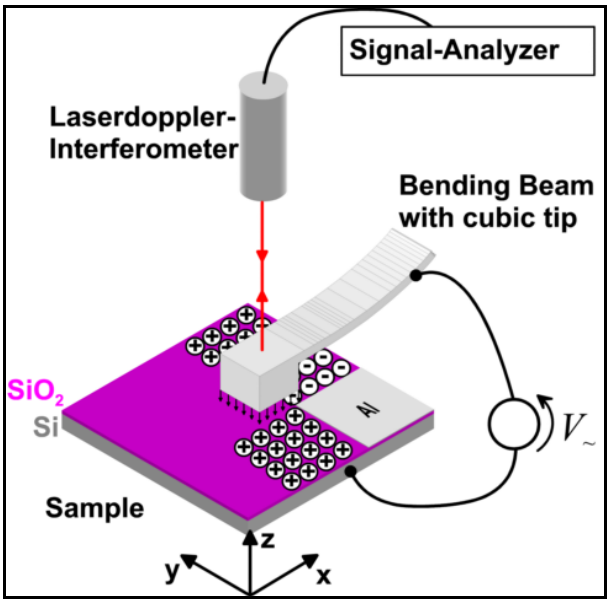

Figure 4: Scheme of the realized electrostatic field sensor

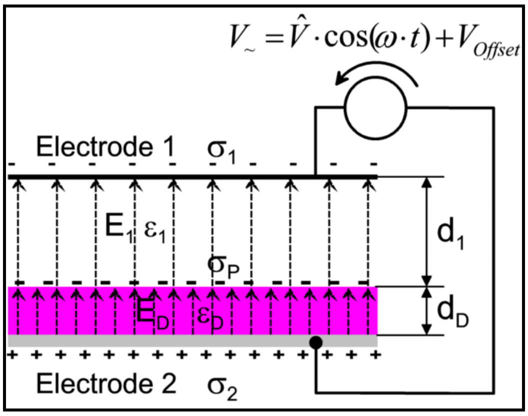

Figure 5: Simplified model of a plate capacitor with a dielectric layer

To characterize the behavior of charges on dielectric layers in the region of driving or sensing electrodes of capacitive MEMS a measurement technique was developed that is related to the KPFM. Figure 4 shows a scheme of the realized electrostatic field sensor. It consits of a bending beam with a cubic tip whereby the lower surface is the sensing area with a size of about 50 µm x 50 µm. A sinusoidal voltage with the frequency ω and an adjustable offset voltage is applied between the sample and the beam. The resulting electrostatic force on the sensing area can be calculated on base of the simplified model shown in figure 5. Because of the assumption of a homogeneous field (i.e., no electrostatic interaction with the adjacence) the plate capacitor has to be electrically neutral, i.e.

$$\sigma_1 + \sigma_2 + \sigma_P = 0 \qquad (1)$$

Furthermore the Kirchhoff's law is valid and the applied voltage divides into

$$V_{\sim} = E_1 \cdot d_1 + E_d \cdot d_d = \hat{V} \cdot \cos(\omega \cdot t) + V_{Offset} \tag{2}$$

Using the equations 1 and 2 and the commonly used equation for the electrostatic force the force on the sensing area (electrode 1) can be expressed as

$$F = -\frac{E_1 \cdot Q_1}{2} = \frac{1}{2}\varepsilon_0 \cdot \varepsilon_1 \cdot E_1^2 \cdot A \tag{3}$$

$$F = \frac{\varepsilon_0 \cdot \varepsilon_1 \cdot A}{2 \cdot (\frac{d_D \cdot \varepsilon_1}{\varepsilon_D} + d_1)^2} \cdot [\frac{\hat{V}^2}{2} \cdot (1 + \cos(2 \cdot \omega \cdot t)) + 2 \cdot \hat{V} \cdot V_{Offset} \cdot \cos(\omega \cdot t)$$
$$+ 2 \cdot \hat{V} \cdot \frac{d_D \cdot \sigma_P}{\varepsilon_0 \cdot \varepsilon_D} \cdot \cos(\omega \cdot t) + V_{Offset}^2 + (\frac{d_D \cdot \sigma_P}{\varepsilon_0 \cdot \varepsilon_D})^2 + 2 \cdot V_{Offset} \cdot \frac{d_D \cdot \sigma_P}{\varepsilon_0 \cdot \varepsilon_D}] \tag{4}$$

Because of the linear spring stiffness of the bending beam the deflection of the tip is proportional to the force (4). Consequently, the beam deflects statically and oscillates at the frequencies ω and 2 ω. The velocity of the motion is measured by the Laserdoppler-Interferometer. The signal analyzer calculates the FFT and integrates the signal to obtain the deflection amplitudes vs. frequency. Using the amplitude at the frequency ω the offset voltage V_{Offset} is controlled that way that equation 5 is fullfilled valid and the expression of the electrostatic force simplifies to equation 6. Now the beam oscillates only at the frequency 2 ω and the deflection amplitude depends on d_1. It is used to control the distance between sensing area and sample surface.

$$V_{Offset} = -\frac{d_D \cdot \sigma_P}{\varepsilon_0 \cdot \varepsilon_D} \tag{5}$$

$$F = \frac{\varepsilon_0 \cdot \varepsilon_1 \cdot A}{2 \cdot (\frac{d_D \cdot \varepsilon_1}{\varepsilon_D} + d_1)^2} \cdot \frac{\hat{V}^2}{2} \cdot [1 + \cos(2 \cdot \omega \cdot t)] \tag{6}$$

The applied offset voltage is used to calculate the charge density at the surface of the dielectric layer in the range of the sensing area

$$\sigma_P = -\frac{V_{Offset} \cdot \varepsilon_0 \cdot \varepsilon_D}{d_D} \tag{7}$$

First measurement results are obtained with the realized setup shown in Figure 6. Figure 7a shows a top view of the scanned section of the sample. It consists of Si with 300 nm thermal SiO_2 and sputtered Al areas on top of the SiO_2. The figures 7b-d show the measured charge distribution after charging the Al area to several voltages. While scanning over the Al area the charged voltages are obtained and even on the adjacent SiO_2 an offset voltage could be detected. This is caused by charges on the dielectric layer which might be deposited by ionization of the ambient air and the reorientation of dipols (mainly water molecules) due to the high electric field on the sample surface.

This new measurement method will be used to characterize the development and the behavior of remanent charges on insulating materials in connection with electrode structures. The goal is to deduce design rules and the choice of materials for MEMS fabrication.

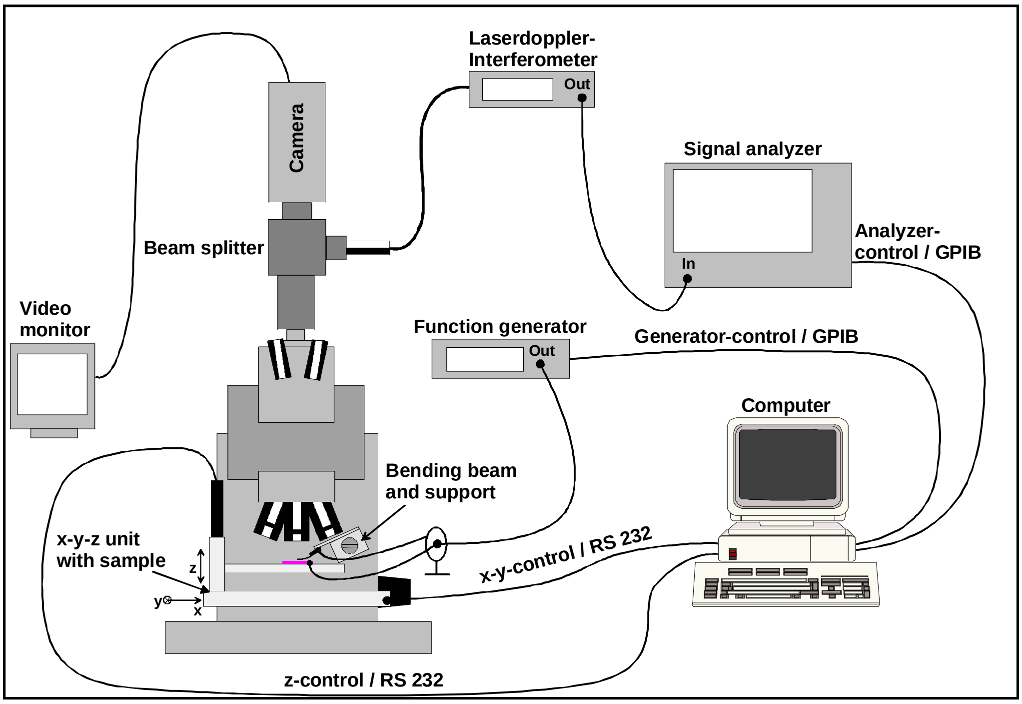

Figure 6: Realized measurement setup

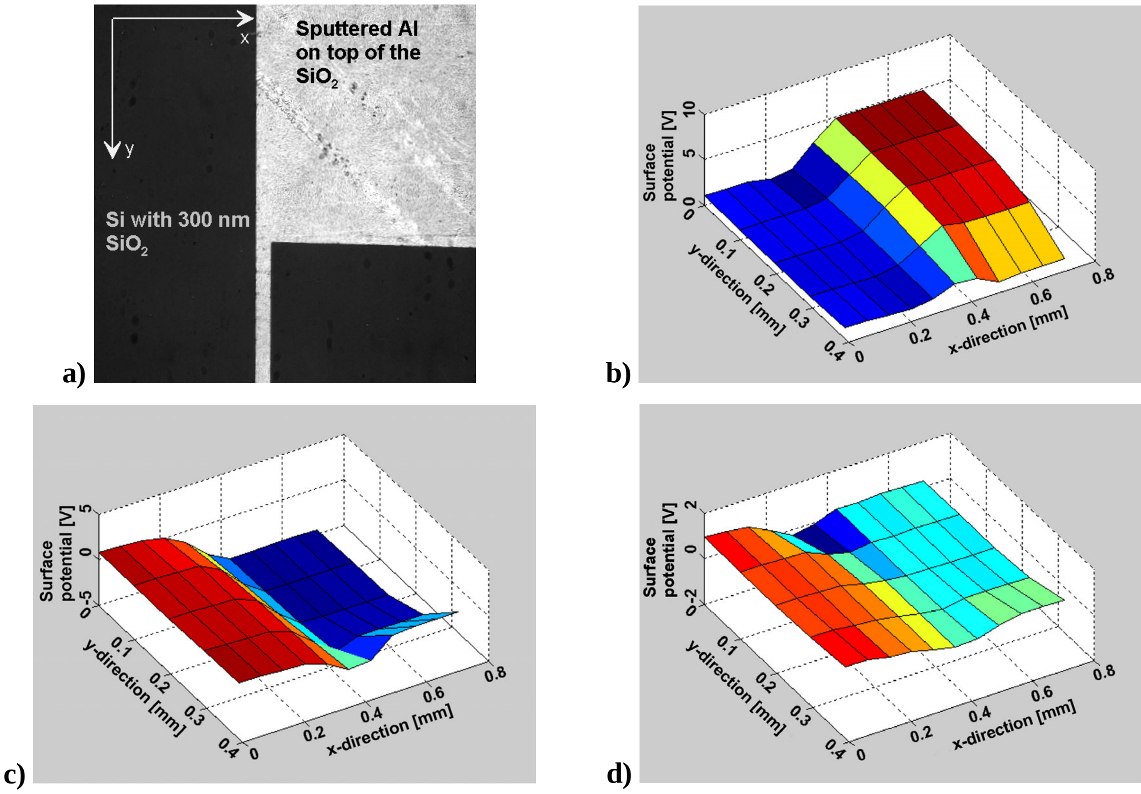

Figure 7: Measured charge distribution, a) used sample, b) Al charged to +5 V, c) Al charged to –5 V, d) Al charged to 0 V

References

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[2] Hülz, H.: *Elektrische Charakterisierung der Oberfläche ferroelektrischer Schichten*, Dissertation, Dresden 1998

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