Capacitive Strain Sensor Based on Transparent Oxide Thin Films

Cosmina Ghinea and Andreas Klein
Technische Universität Darmstadt, Department of Materials and Earth Sciences, Surface Science Division,
Petersenstrasse 32, 64287 Darmstadt, Germany

1. Introduction

Many advanced industrial applications require high-performance strain sensing functional modules consisting of sensors and interface electronics. Capacitive sensors present numerous advantages such as high sensitivity, low temperature dependence, low noise, large dynamic range and potential monolithic integration with CMOS circuits [1]. In the 1960s, the development of capacitive gauges starts in order to measure strains at high temperatures with good long term stability [2]. The main applications were in the aerospace and power industries. In these gauges, air is used as the dielectric between two plates and the variation in the capacitance was due to the change in device geometry [3]. Later Arshak et al. [4] have developed a highly sensitive thick film capacitive strain sensor. The device configuration was based on a multi–layered metal-resistor-metal (MRM). A metal oxide paste was used as a piezoresistive material. The resulting device had a gauge factor comparable to silicon strain sensors. In the automotive industry the pressure sensors are very customary. Therefore, the study of capacitance effects in mechanical transducers has been undertaken. Using thick film technology a low-cost pressure sensitive device and an efficient signal conditioning circuitry has been developed [5]. In this case the dielectric-sensing material was based on commercial Cermet and a PZT paste. The relative performance of the pressure sensor was compared in terms of sensitivity, repeatability and hysteresis. Capacitive strain sensors for biomedical applications were the very first technology drivers to stimulate research in this direction. Modern medical science has emerged with the need to monitor physiological functions (i.e. intravascular pressures, intraocular pressures, etc.). One area of need is a system that will assist orthopaedic surgeons with the diagnosis of spinal fusion. To fulfill this need an interdigitated finger MEMS-based capacitive bending strain sensor was developed [6]. Deep reactive ion etching has been used to obtain the interdigitated fingers from highly doped boron silicon wafer with a low resistivity. The capacitance output increased as an inverse function of the spacing between the interdigitated fingers.

In this work, a complety transparent capacitive strain sensor using thin film technology is presented. The dielectric material barium-strontium-titanate was chosen as active material while indium doped tin oxide was used as electrode. In order to perform the electromechanical characterizations of these pasive sensors, an experimental set-up based on the 4-point bending theory was used. The change in capacitance due to strain was also analysed by varying the DC bias and measurement frequency.

2. Theoretical considerations

The sandwich capacitors are defined as a passive electronic component consisting of a pair of parallel electrodes separated by a dielectric material. When an external voltage is applied across the electrodes, a static electric field is present in the dielectric. The dielectric material will store energy and produce a mechanical force between the electrodes. The measure of stored electrical energy is named capacitance C which is given by $C = \varepsilon_r \varepsilon_0 A/d$ if the permitivity of the free space ε_0, the permitivity of the dielectric ε_r, the active area of the parallel capacitor *A* and the distance between the electrodes (dielectric thickness) *d*, are known.

If a mechanical strain is applied on the capacitor it will be deformed and a variation in the capacitance will emerge. Arshak named this effect “the piezocapacitive effect” [7]. The change in capacitance arises from two reasons : a) geometric change and b) change in the permittivity of the dielectric material. Fig. 1 shows the possible changes which can appear in a parallel plate capacitor.

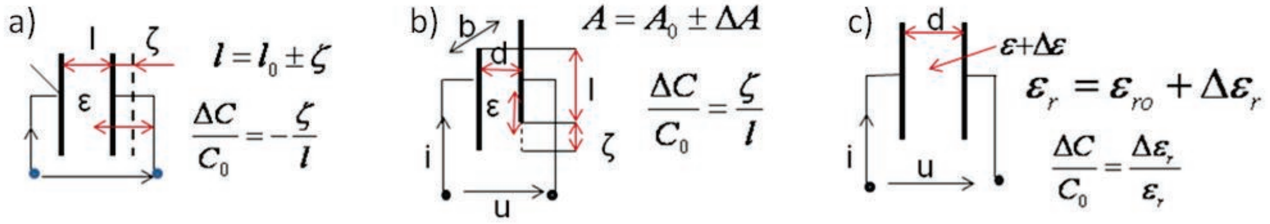

Fig.1: Possible capacitance changes caused by (a) variation of distance between electrodes; (b) variation of active capacitor area; (c) variation of permitivity of dielectric material.

Taking into consideration all changes which can appear in the capacitor by appling a strain, the total change of capacitance is calculated as $\delta C/C = \delta\varepsilon_r/\varepsilon_r + \delta A/A - \delta d/d$. This expression can be simplified by the use of Poisson’s ratio, which links the area and thickness changes [8]. The gauge factor (GF) is calculated according to: $GF = (\delta C/C)/\varepsilon$, where ε is the strain.

3. Experimental

This work was focused on developing a completely transparent capacitive strain gauge using the thin film technology. Therefore, by selecting the materials for our device two criteria were taken into consideration: 1) materials should present good electric/dielectric properties and 2) should have a high transparency for visible light. (Ba,Sr)TiO_3 (BST) is a highly non-linear dielectric material which can be used in different electronic applications [9]. It has a high transparency for visible light due to its energy gap of >3.2 eV [10]. Indium-tin oxide (ITO) is a degenerately doped semiconductor, which is a commonly used transparent conductive oxide electrode [11]. Recently, the electrical functionality of ITO/BST/ITO capacitors has been reported [12]. It was suggested that due to the large energy gaps of both BST and ITO, the combination of these materials is very promising for applications in transparent electronics. The particular feature of the ITO/BST contact is that charge injection is easily possible, as there is no barrier for electron injection at the interface. Despite the large leakage currents, the ITO/BST/ITO structure still exhibits a capacitive behaviour.

The thin film capacitors were deposited onto Si/SiO_2 substrates by radio frequency magnetron sputtering in Ar and Ar/O_2 gas mixtures. Substrate temperatures were 400°C for ITO and 650°C for BST, repectively. The preferred structure was obtained using shadow masks, which were mounted in air. The film thickness was determined using white light interferometry. The measured thickness was 200 nm for electrodes and 300 nm for the dielectric material. The geometrical arrangement of the layers is depicted in Fig. 2.

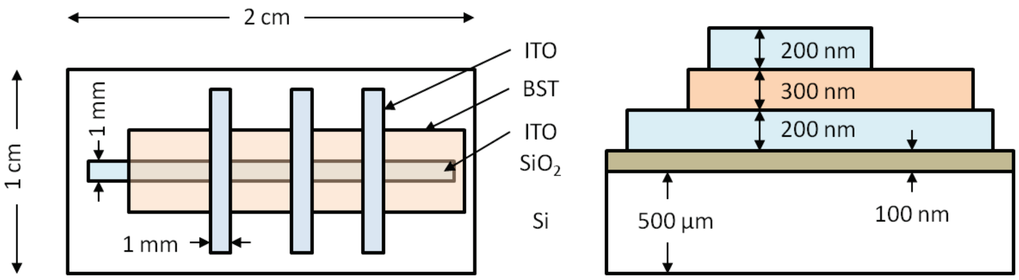

Fig.2: Test configuration of ITO/BST/ITO paralell plate capacitor structure (left) top view; right (side view).

In order to perform the electromechanical characterizations of the passive sensors, an experimental static set-up (Fig.3) based on the 4-point bending theory was used. The 4-point set-up confers strain symmetry and good static stability due to the fact that the part of the outside beam is free from external forces and this means that the shear strain is zero outside the outer knives. Between the inner knives it is a constant moment which gives a linear variation in strain only with z axis. Using this set-up it was possible to apply a tensile micro-strain on the samples. The strain has been calculated using the formula from [13] and knowing the substrate thickness and the displacement of the micrometer.

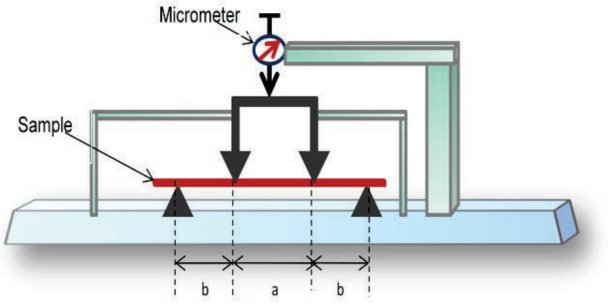

Fig. 3. Schematic 4-point arrangement for the measurements of the strain response of the capacitors. The thin film capacitor is located at the lower side of the sample.

The capacitance of the samples was measured with a 4294A Agilent precision impedance analyzer at room temperature and at normal pressure. The contacts of the samples were made with copper wires which were attached to the ITO electrodes area with silver paste which was dried in air at room temperature.

As already mentioned, in the case of piezocapacitive effect the change in the capacitance could arise due to a change in the sample geometry combined with a change in the material dielectric permittivity. While geometrical changes are not expected to result in a high sensitivity, it is proposed that the change in the dielectric permittivity can lead to high value of the gauge factor, which are in the range of those observed with piezoresistive sensors [14, 15]. This strain gauges showed good mechanical characteristics with gauge factors between 10-200.

4. Sensor performance

Figure 4 shows plots of the capacitance and dissipation factor vs. frequency for the ITO/BST/ITO capacitor. It can be noticed that the dissipation factor decreases till around 5 kHz as the frequency increases. In the range 5 kHz to 250 kHz, the dissipation factor increases gradually. The capacitance slowly decreases with increasing frequency up to ~40 kHz.

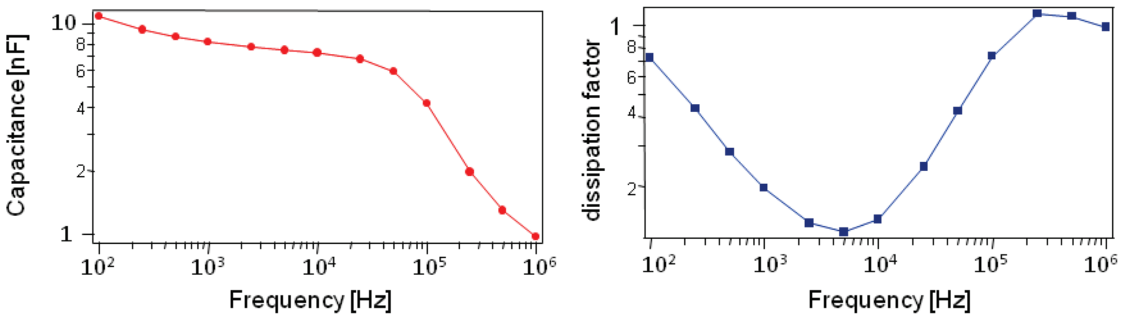

Fig.4.(left) Capacitance vs. Frequency; (right) Dissipation factor vs. frequency. Both data sets were recorded with zero strain and without applied dc voltage.

The frequency dependent behaviour of the ITO/BST/ITO capacitor in Fig. 4 is consistent with a Debye-like relaxation behaviour. A frequency dependent phenomenon means that the DC-related components will also be present. According to the Debye model the DC-component can be seen as a parallel resistance across the device, which is constant with the frequency and its dissipation factor (tan δ) has a value which decreases with frequency because $\tan\delta = 1/\omega RC$. The relaxation behaviour is attributed to the low carrier mobility in BST [12]. At low frequency, the injected charge carriers in the BST follow the ac signal leading to a variation of the space charge in the film. At higher frequency the carrier mobility is too low and the space charge density remains constant. Hence the resulting capacitance is defined by the distance between the electrodes, which is the film thickness. The capacitance at higher frequency corresponds well with the capacitance of BST films with non-injecting electrodes [9], confirming this interpretation of the frequency dependent measurements.

The strain effect on capacitance and the derived gauge factor are illustrated in Fig. 5. It can be noticed that capacitance decrease with increasing strain. The gauge factor is large for low strain and decreases with increasing strain. Its magnitude is, however, larger than expected for a pure geometrical effect. The origin of the capacitance is not completely clear yet. Two different contributions are envisaged: (i) a change of permittivity in dependence on strain; (ii) a change of carrier mobility in dependence on strain. At the moment we believe that the sensor effect is not caused by a change of permittivity, as we have not yet observed large changes in capacitance with Pt electrodes. A change of carrier mobility in dependence on strain would be similar to a piezoresistive effect. Such effects are not expected for (Ba,Sr)TiO_3 films, which have a cubic symmetry with an inversion center. The symmetry is lifted, however, when an electric field is applied to the electrodes leading to the observation of acoustic resonances in the GHz range [16].

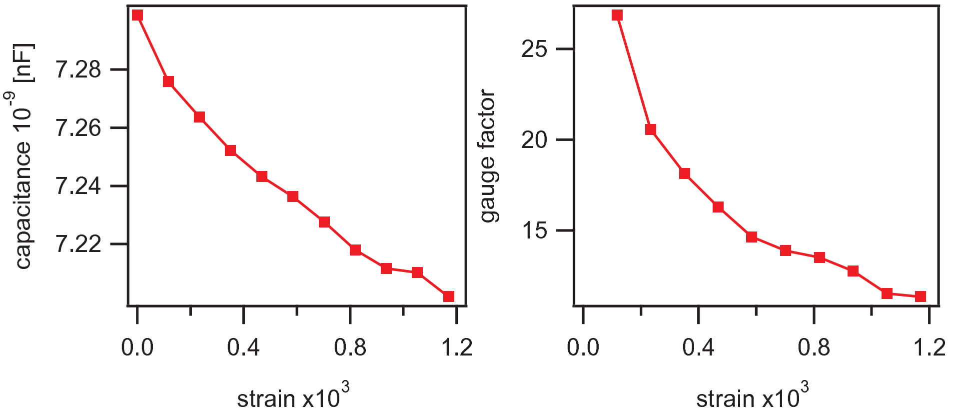

Fig. 5: (left) capacitance vs. strain measured at 10 kHz without applied dc voltage; (right) gauge factor calculated from the capacitance vs. strain.

Applying a dc voltage across the two ITO electrodes in addition to the ac signal for measuring the capacitance of the capacitor changes the capacitance significantly (Fig. 6). This is related to the strong dependence of the BST permittivity on applied electric field [9]. In contrast to the typically symmetric decrease of capacitance with applied positive and negative voltage, a highly asymmetric C-V dependence is observed with ITO electrodes. The application of larger negative voltages can even lead to a large increase of capacitance. This is related to the strong charge injection at the top ITO electrode [12], which leads to an effectively thinner capacitor. The ITO/BST/ITO structure still exhibits a capacitive behaviour, as the mobility of the charge carriers in BST is very low [12]. The asymmetric behaviour is explained by the different properties of the bottom ITO electrode, as the ITO substrate is modified during the high temperature deposition of the BST layer. The effect of strain is also included in Fig. 6. Depending on dc voltage, a strong increase or decrease of capacitance is observed. The measurements in Fig. 6 are recorded using a measurement frequency of 10 kHz. The maximum change of capacitance with strain is observed for a bias voltage of -3 V. The 10% change of capacitance for a 0.1% strain corresponds to a gauge factor of ~100. As suggested by Fig. 4, the behaviour will also depend on the measurement frequency.

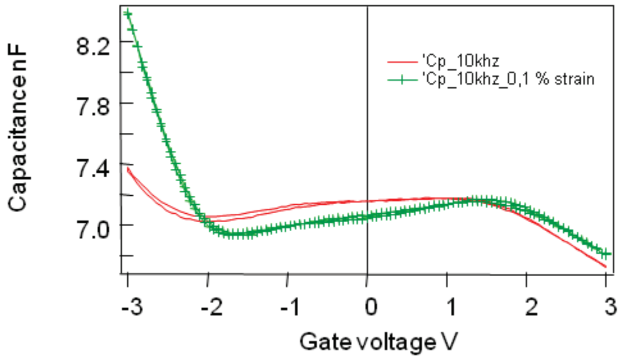

Fig.6 Voltage dependence of the capacitance of an ITO/BST/ITO capacitor measured at 10 kHz without and with 0.1% strain.

5. Summary

In this study, the behaviour of capacitive strain gauges based on ITO/BST/ITO thin film structures was investigated. The strain effect on capacitance-frequency and capacitance-voltage was analyzed. It was observed that the strain has a significant effect on the C-V behaviour. Also, it has been shown that the strain produce a change in the dielectric permittivity of the material. Applying a tensile strain a decrease or increase in dielectric permittivity has been noticed depending on the applied dc voltage. Further developments will include identification of a better transparent substrate material which remains stable during BST deposition. In order to obtain fully transparent strain gauges for the deposition on window glass e.g., also lower dielectrics which can be prepared at lower substrate temperatures are desirable.

Acknowledgement

This work has been supported by the Land Hessen within the LOEWE research center on Adpatronic, AdRIA. The authors also like to thank Shunyi Li and Robert Schafranek for assistance during measurements.

References

[1] L.L. Chu, et al., J. MEMS 11 (2002), 489-498.

[2] E. Procter et al., *Capacitive Strain Gauges, Strain Gauge Technology*, Elsevier, 1982, pp. 291- 325.

[3] A. Taroni, *Capacitive sensors*, in: M. Prudenziati (Ed.), *Thick Film Sensors*, Elsevier, 1994, pp. 245-258.

[4] K.I. Arshak et al., Int. J. Electron. **77** (1994) 387 – 399.

[5] K.I. Arshak et al., Composites Science and Technology **65** (2005) 757-764.

[6] J. Aebersold et al., Journal of Physics: Conference Series **34** (2006) 124-129.

[7] K.I. Arshak et al., Sensors and Actuators 79 (2000) 102-114.

[8] A. Arshak et al., Sensors.Actuat. A-Phys. **122** (2005) 242

[9] S. Gevorgian, IEEE Microwave Magazine, **10** (2009) 93–98.

[10] K. van Benthem, C. Elsässer, R.H. French, J. Appl. Phys. **90** (2001) 6156.

[11] T. Minami, Semicond. Sci. Technol. **20** (2005) S35.

[12] S. Li, C. Ghinea, T. Bayer, M. Motzko, R. Schafranek, A. Klein. J. Phys.: Cond. Mat. (2011) (in press).

[13] P. Alpuim et al., Vacuum **83** (2009) 1279-1282,

[14] K.I. Arshak, et al., J. Mater Sci: Mater. Electron **17** (2006) 767-778

[15] O.J. Gregory et al., Thin Solid Films **518** (2010) 5622-5625

[16] A. Giere et al., Frequenz **62** (2008) 52.