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Stress in three-dimensionally integrated sensor systems

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ABSTRACT

The ability to incorporate gas sensing devices into always-on wearable technology such as smart phones, tablets, and wrist watches will revolutionize the environmental health and safety industry by providing individuals with a convenient way to detect harmful chemicals in the environment. Although thin metal oxide films have shown their gas-sensing ability, several challenges must still be overcome in order to enable full CMOS integration with a reduced cost of production. A micromachined tin oxide (SnO_2) gas sensor on a suspended membrane is presented and its operation, heat flux away from the membrane, and stress generation are analyzed. The device operates based on the adsorption of oxygen at its surface when heated to temperatures between 250 °C and 550 °C, where the presence of oxygen ions results in the formation of a depletion region inside the SnO_2 layer. The thermal flux away from the heated membrane is calculated, resulting in a total power loss of 32.5 mW. In this calculation, the heat flux through the membrane as well as the air conduction and radiation are accounted for. The stress through the membrane is calculated to be around 500 MPa to 550 MPa with a maximum displacement of 6.6 μm through its middle. The intrinsic stress through the tin oxide layer is analyzed during film growth using the Volmer-Weber model, resulting in a 200 MPa stress and a 1.69 J/m^2 surface free energy of the deposited material. The use of spray pyrolysis, a CMOS-friendly deposition technique, in order to deposit the SnO_2 layer on the membrane resulted in a total thermo-mechanical stress of 380 MPa.

1. Introduction

The presence of multiple gases in our vicinity shapes our perception of the environment. Although the human nose serves as a sensor or detector of hundreds of different odours, it fails when absolute gas concentrations or odourless gases require detection. The ability to electrically detect these gases is a topic of extensive research and has found applications in areas related to increased comfort, such as climate controls in buildings and vehicles, but also in safety. The feasibility to detect toxic and harmful gases in our environment through hand held and wearable devices is of particular significance triggering substantial research. In addition, fabrication and process controls, and laboratory analytics can be made more affordable with cheaper gas sensing equipment [1].

Currently, a variety of gas sensing principles are being implemented in industry, e.g. semiconductor, optical, thermal conductivity, quartz microbalance, catalytic, dielectric, electrochemical, and electrolyte sensors [1]. Recent discoveries in the use of metal oxides as gas sensing materials are at the forefront for enabling significant progress in moving away from bulky sensor architectures [1–10]. The miniaturization of electronic devices has proven to be essential, while the gas sensor field is still lagging behind the overall progress of CMOS and MEMS devices. Two materials have been validated to exhibit all the properties required for a good gas sensing performance, namely zinc oxide (ZnO) [11–14] and tin oxide (SnO_2) [15–17], while others such as indium tin oxide (ITO), In_2O_3, CdO, $ZnSnO_4$, NiO, etc. have also been widely studied [13]. These studies attempt to drive research towards the fabrication of cheap, small, and user-friendly devices with a high sensitivity, selectivity, and stability with respect to the desired application. However, before true integration of gas sensor components inside gadgets such as smart phones and wrist watches can be achieved, several challenges must be overcome:

- Until recently, gas sensor fabrication was not compatible with that of a conventional CMOS process sequence, which is essential for its integration into hand-held electronics. Currently, the deposition of metal oxide materials is being performed using several techniques such as chemical vapor deposition [18], sputtering [19], pulsed-laser deposition [20], sol–gel process [21], rheotaxial growth and vacuum oxidation [22], and spray pyrolysis [15].
- Thin metal-oxide layers can only act as gas sensors when heated to temperatures between 250 °C and 550 °C, which means that a micro-hotplate must accompany each sensor. The integration of the hotplate and the sensor with the required analog and digital circuitry, as shown in Fig. 1, is necessary. Since metal oxides detect various gases, a sensor array is implemented in order to introduce selectivity in the sensor unit [23].

As already depicted in Fig. 1 the operation of a smart gas sensor implies the ability to detect a multitude of hazardous gases in the environment, for which multiple sensor circuits are required. The analog signals

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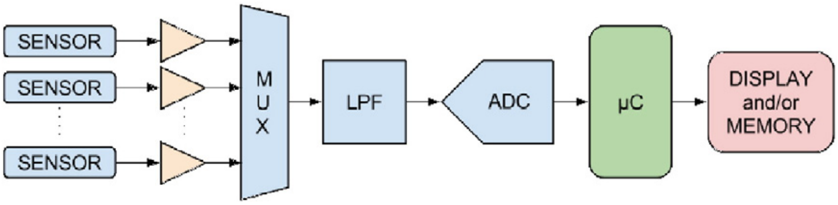

Fig. 1. Sensor unit showing a sensor array with interface electronics blocks, which include the amplifiers, multiplexer (MUX), low-pass filter (LPF), analog to digital converter (ADC), microcontroller (μC), and DISPLAY and/or MEMORY.

from these sensors are passed through an amplifier to a multiplexer. The output from the multiplexer is sent through a low-pass filter (LPF) and an analog to digital converter (ADC) before the signal can be analyzed with a microcontroller (μC) and eventually displayed or stored [7]. Although the major part of the electronics consists of analog and digital CMOS circuitry, the most complex component for integration and manufacturing is the sensor itself.

In this work several aspects of a typical tin oxide gas sensor are analyzed with the aid of simulation in order to understand the sensor performance and reliability with regard to thermal dissipation and stress build-up. First, the gas sensor analyzed in this work and the sensing mechanism itself are described. A model for a compact thin-film SnO_2 sensor is presented for the detection of ambient H_2, which is an important component in smoke and fire detectors. Afterwards, the reliability of the suspended membrane is discussed, where the thermal dissipation of the device is analyzed and essential design components are given in order to minimize the power dissipation. The stress build-up in the membrane is also discussed, followed by an analysis of the stress build-up in the metal oxide during deposition, according to the Volmer-Weber growth mode [24].

2. Metal oxide sensor operation

At increased temperatures, oxygen is adsorbed at the metal oxide surface by trapping electrons from the bulk material [25]. The result is an overall decrease or increase in the metal oxide resistance, depending on whether the material is n-type or p-type, respectively. The band bending at the metal oxide/ambient interface is depicted in Fig. 2. The introduction of a target gas in the atmosphere causes a reaction with the oxygen, removing it from the interface and reducing the band bending effect and thereby the overall resistance [26].

The thickness of the depletion layer is in the order of the Debye length, defined as

$$\lambda_D = \sqrt{\frac{\varepsilon \cdot k_B \cdot T}{q^2 \cdot n_c}}, \tag{1}$$

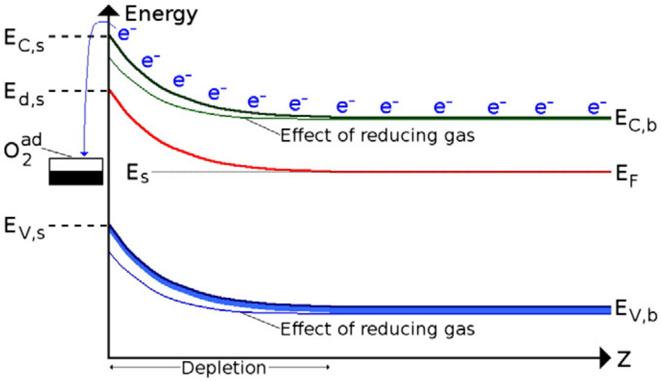

Fig. 2. Schematic representation of the band bending effect caused by oxygen adsorption and subsequent introduction of a reducing gas.

where ε_0 is the free space permittivity, q is the elementary charge, and n_c is the carrier charge density.

Even though plenty of effort has been directed towards understanding the gas sensing function of metal oxide materials, the exact chemistry of the sensing process is complex and not yet exhaustively understood [27]. The thin film can either be porous, where sensing occurs at the grain-level and between individual grains, or compact, where sensing occurs on the bulk material surface, as depicted in Fig. 3. A porous film is more complex to deposit when compared to a compact thin film, usually involving a sol–gel technique followed by a gelation step [27]. More recently, rheotaxial growth and vacuum oxidation was used to deposit porous films [22]. A compact metal oxide thin film can be deposited using a variety of techniques, including spray pyrolysis which has recently gained traction due to its cost-effectiveness and integration within a standard CMOS processing sequence. This study concerns itself with a compact tin oxide metal film, deposited on a micromachined suspended membrane.

2.1. SnO_2 gas sensor geometry

The geometry of the sensor studied here is depicted in Fig. 4. The membrane has an area of 200 μm × 200 μm while the active sensor area is 100 μm × 100 μm. The beams connecting the membrane to the wafer are 100 μm long and 20 μm wide. The thicknesses of the membrane and the beams are 4 μm with a microheater sandwiched between a 2 μm SiO_2 layer at the bottom and a 2 μm Si_3N_4 layer at the top. The

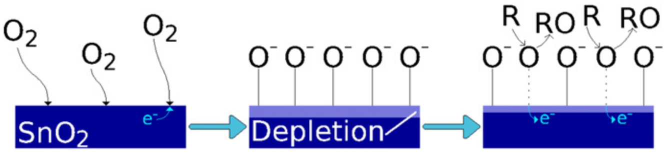

Fig. 3. Gas sensing function for a compact tin oxide film. The reaction occurs only at the top surface of the deposited tin oxide. The symbol R refers to a reducing gas.

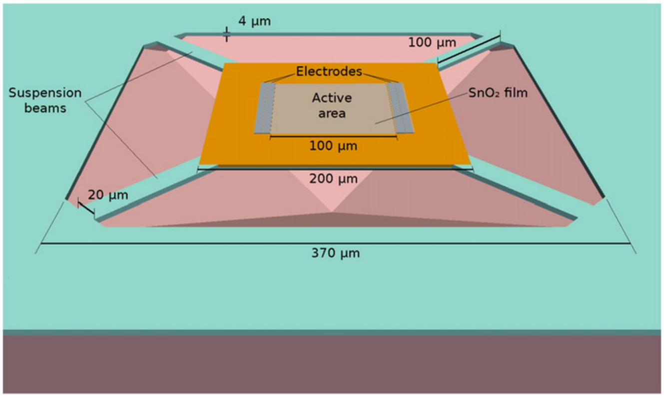

Fig. 4. Setup of the integrated gas sensor on top of a micromachined suspended membrane.