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From stress sensor towards back end of line embedded thermo-mechanical sensor

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ABSTRACT

In the context of Back-End of Line (BEoL) roadmap, dimension reduces, density integration increases and new materials are introduced. These points associated to manufacturing thermal budget could induce mechanical failures. Thus, a metallic *in situ* sensor was developed to study residual stress on a single metal level: using standard CMOS BEoL processing on 8″ silicon wafer, aluminum thin film is patterned on dielectric layer. The sensor is composed by arms and a flexible beam that are fixed to anchors. As the structure is released from its surrounding layer, the relaxation of residual stress induces a displacement of flexible beam. Therefore, the measurement of this displacement allows determining the initial residual stress. Using this structure, the purpose of this paper is not only to determine the residual stress state, but also the thermo-mechanical properties: coefficient of thermal expansion and thermal conductivity. For that reason, new designs are released to address electrical polarization and thus to locally heat this sensor by Joule effect. Due to thermal expansion, the flexible beam will move. The thermo-mechanical properties were determined by coupling SEM electrical nano-probing (displacement of flexible beam and electrical resistance as a function of applied current) with analytical modeling and Multi-physics Finite Element Method (FEM). As a result, a tensile stress state of 190 MPa in arm direction is identified in the aluminum thin film. The coefficient of thermal expansion of $22.5 \times 10^{-6}\ K^{-1}$ and thermal conductivity of 190 W/(K m) were identified, in agreement with literature.

1. Introduction

Following transistor downscaling, the Back-End of Line (BEoL) of integrated circuits becomes more and more complex with higher integration density and introduction of new metallic – intermetallic dielectric materials [1]. As these materials have different thermo-mechanical properties [2], manufacturing thermal budget induces mechanical stress that could bring about mechanical failures [3]. For that reason, metallic *in situ* stress sensor was developed [4,5]. Using standard CMOS BEoL processing on 8″ wafer, aluminum thin film is patterned on dielectric layer. The stress sensor is composed by metallic arms and a flexible beam surrounded by dielectric. As the structure is released from its surrounded layer, the relaxation of residual stress induces a displacement of the flexible beam. Using an analytical model [6], the measurement of this displacement allows the determination of residual stress in accordance with Finite Element Method (FEM) [7]. This approach is validated by experimental verification using X-ray technique and Stoney formula [8,9]. This sensor turns out to be a local, fast and fine tool for material characterization under micron scale. More options are developed using an additional electrical polarization. Direct observation of stress gradients in aluminum interconnect metallization is done [10]. Using CMOS–MEMS fabrication process, Kelvin probes [11] and thermal switch [12] are created.

The purpose of this paper is to use a metallic *in situ* stress sensor (Section 1) not only to determine the residual stress state, but also the thermo-mechanical properties: coefficient of thermal expansion and thermal conductivity. These parameters need to be monitored. They reveal great importance in thermo-mechanical finite element analysis of MEMS [13,14] and prediction of mechanical failure in BeOL [15].

The initial design of stress sensor is modified to allow electrical polarization. Thus, the sensor is locally heated by Joule effect using *in situ* SEM electrical nano-probing (Section 2). Then, due to thermal expansion, the flexible beam will be displaced. By coupling experiments (displacement of flexible beam and the electrical resistance as a function of the applied current, Section 2) with FEM and analytical modeling (Section 3), a gradual approach is developed to determine these parameters:

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- Residual stress is identified using the position of the flexible beam after release (FEM structural mechanics module).
- From electrical measurement, the global temperature of the sensor is calculated with Senturia's model [16]. This identified temperature is used to determine the coefficient of thermal expansion by fitting the displacement of the flexible beam (FEM structural mechanics and thermal expansions modules).
- Using this coefficient of thermal expansion, the thermal conductivity is extracted (FEM structural mechanics, Joule heating and thermal expansions modules). Here, the temperature is induced by Joule effect and not calculated from the analytical model.

Thin film properties could be determined by other local methods. In particular, nano-indentation coupled with FEM is used to determine the complete stress strain behavior of thin films [17,18]. The nano-indentation technique evolves to carry out measurement in temperature [19,20] and to extract mechanical properties under small indentation depths [21,22]. But, the extraction of material properties using this technique should not be practicable directly in BEoL due to geometrical confinement, thin film and substrate interaction, and indent size effect. Some tests on free-standing thin film (membrane and cantilever) [23–27] allow Young's modulus, Poisson's coefficient, yield stress, residual stress and coefficient of thermal expansion determination. This work is complementary to these methods. The advantage is to have the sensor directly embedded in the BEoL.

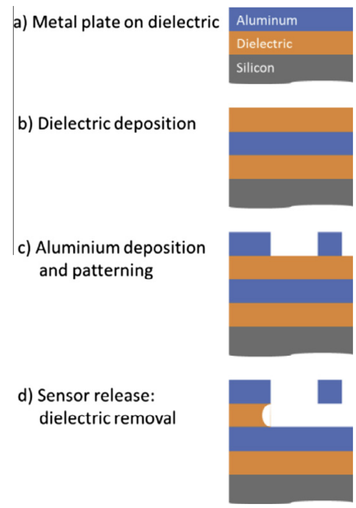

Fig. 2. Process flow of "H" stress sensor (AA′ cross section from Fig. 1a).

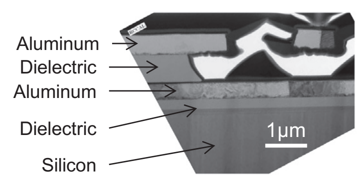

Fig. 3. SEM cross section AA′ (Fig. 1a) of the released sensor.

2. "H" mechanical stress sensor

The "H" sensor (Fig. 1a) consists of a block, two anchors, a flexible beam and arms. The presented sensor is manufactured using standard CMOS process. The size of arms and flexible beam are 1 μm width and 30 μm length. Anchors and block measure respectively 80 × 80 μm^2 and 20 × 28 μm^2. The anchors are used as fixed part (attached to the substrate) and are linked to the arms. The arms and flexible beam are free. The arms contact or get longer due to stress or temperature. Then the flexible beam will moved. The block, also attached to the substrate, is used to easily measure the flexible beam deviation.

The process flow is performed on 8″ silicon substrate. An aluminum plate is deposited on dielectric (Fig. 2a). A second dielectric layer is deposited on the metal plate (Fig. 2b). Then aluminum thin film, corresponding to sensor layer, is deposited (550 nm thick) and patterned (Fig. 2c). The position of patterned flexible beam corresponds to a referential point (zero deviation, $d = 0$, Fig. 1a).

A process is developed to just release arms and flexible beam from surrounding dielectric without stiction (Fig. 3). The block and anchors (Fig. 1a) are not released due to their large widths and so are attached to the substrate. Once release process is done, the sensor is a fixed–fixed structure: the arms are attached to the anchors. The sensor is also suspended: the aluminum arms and flexible beam are surrounded by air (Figs. 2d and 3).

As the structure is released, the arms contract or get longer due to respectively initial tensile or compressive stress. Thus, the displacement of arms induces a bending of flexible beam from initial position (Fig. 1b and c). The block is used to easily measure the flexible beam deviation and thus to monitor residual stress. In the following, only the maximum deviation in the middle of the flexible beam is measured. Using FEM, the uniaxial residual stress (in arm direction) is calculated (Section 3b).

Then, the sensor is locally heated by Joule effect. A current is applied through sensor arms as described in Fig. 4, so that only the suspended aluminum is heated. Joule effect releases heat and induces a thermal expansion of sensor arms. The position of the flexible beam starts from release state (negative or positive due to

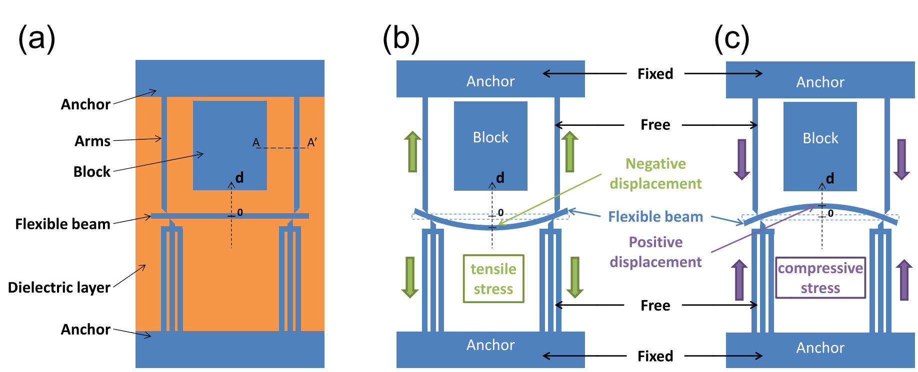

Fig. 1. "H" stress sensor after standard process flow (a) and released in the case of initial tensile stress (b) and compressive stress (c). Fat arrows indicate the displacement induced by stress relaxation.