Simulation of capacitive type bimorph humidity sensors

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Abstract. FEM modeling of recently developed Silicon/polymer bimorph micro-cantilever structures, applied as capacitive type humidity sensors, is presented. In these structures, the expansion of the overlying polymer in the presence of water vapors forces the silicon cantilever to bend resulting in a change of device capacitance. Experimental behavior is approximated by taking into account the stress induced in the cantilever due to the polymer swelling. Simulation results are in good agreement with experimental values. The FEM model developed facilitates the design and optimization of the cantilever beam sensors.

1. Introduction

Silicon/polymer bimorph micro-cantilever structures have recently attracted attention as chemical sensors. First introduced in 1994 [1], silicon micro-cantilevers have been shown to be able to detect minute quantities of chemical species with sensitivity exceeding that of traditional quartz crystal microbalance (QCM) and surface acoustic wave (SAW) transducers [2]. Recently, the fabrication of freestanding silicon cantilevers at close proximity to the underlying substrate using silicon fusion bonding and dry release of the silicon members in SF₆ RIE plasma was presented [3]. The new process allowed the fabrication of capacitive type humidity sensors by covering the silicon freestanding cantilevers with polyimide. This polymer was chosen for its known hydrophilic behavior and its ease of processing. However, most of the polymeric coatings inherently develop stress during solidification as they shrink due to chemical reaction, solvent evaporation, phase separation or a combination of these [4]. In fact, the adhesion of the polyimide at the underlying silicon layer prevents shrinkage from occurring freely and gives rise to a tensile stress in the plane of the coating. Therefore, as the polyimide-precursor layer is cured at 400°C to perform polymerization, the solvent is evaporated resulting in shrinking of the polymer layer (40% volume loss) and giving rise to a stress-induced upward bending of the silicon cantilever. This initial bent ensures that the device will not stick to the substrate at high humidity levels. As molecules are adsorbed in the polyimide layer stress is induced on the cantilever resulting in the bending of the cantilever and a change in the capacitance between the structure and the substrate.

In this work, finite element (FE) modeling has been used to approximate the Si/polyimide bimorph behavior and to facilitate the design and optimization of the cantilever beams. FE simulations were performed using Coventorware software. Cantilevers of various lengths (ranging from 100µm to 2500µm) have been studied.
Figure 1. Schematic of the capacitive-type humidity sensor. The freestanding silicon member is covered with a polyimide layer.

Figure 2. Top-surface view of the polyimide covered cantilevers. The devices are bent upward due to the polyimide precursor shrinking after curing.

2. Simulation Methodology

Figure 1 is a schematic design of the capacitive type humidity sensor, while figure 2 is an SEM image of an array of cantilevers. The sensor comprises of a freestanding silicon member with a square shaped end, covered with a polyimide layer.

As can be seen in figure 2, all cantilevers exhibit upward bending due to shrinking of the polyimide after curing. At this state, both the stress induced in the cantilevers as well as their deflection obtain a maximum value. During operation, the polyimide layer swells as it is exposed to ambient humidity; the induced compressive stress decreases in value and the cantilever tends to return to its horizontal position, effectively increasing the device capacitance. The value of the initial maximum deflection was measured with a SEM microscope under vacuum conditions or 0% relative humidity, and is used during simulations as a starting point in order to get a first estimate of the film stress. Subsequently, stress values are swept down to 0 effectively simulating the realistic situation where the stress on the cantilever beams decreases because of water molecule absorption. Cantilever with lengths ranging between 100 µm and 2500 µm and 100 µm in width were studied. In figure 3, the exact dimensions of the experimental devices used are depicted.

For the FE simulations, the dimensional models of the cantilever devices were constructed using the geometrical data from the actual sensors. All simulations were performed using the Coventorware software. The material properties [5-6], and geometry parameters are summarized in Table 1.

![Table 1. Material properties and geometrical data.](image)

| (a) Material properties | (b) Geometry parameters |
|-------------------------|-------------------------|
| Young’s Modulus of Si   | 169 GPa                 | Length        | 100 – 2500 µm |
| Young’s Modulus of polyimide | 3.3 GPa               | Width         | 100 µm        |
| Poisson’s ratio of Si   | 0.3                     | Square end side | 200 µm       |
| Poisson’s ratio of polyimide | 0.35                  | Si beam thickness | 2.4 µm       |
|                         |                         | Polymer Thickness | 2.5 µm       |

The MemMech Solver is used to analyze the relation between the internal stress of the polyimide and the deflection of the cantilever. Selection of the appropriate finite element type is a critical point in order to perform accurate and fast simulations. The “Extruded bricks” mesh element type has proved to be the most appropriate in our case. Mesh density was increased until further refinement yielded
less than 1% difference in results. In the case of the 750 µm long cantilever, typical simulation results can be seen in figure 4. In this figure the deflections along the structure are depicted.

Following the estimation of deflections along the cantilever length the MemElectro Solver was employed to calculate the corresponding capacitance values as a function of the applied isotropic stress using the deformed mesh of the MemMech Solver. Thus, a capacitance versus stress curve is obtained for each cantilever geometry.

3. Results and discussion

In figure 5 the experimental values of the initial tip deflections of the cantilevers as measured in 0% RH with a SEM are plotted together with the deflections obtained from the corresponding simulations as a function of $L^2$. The linear relationship observed is in agreement with the case of bilayer structures with different expansion coefficients [7]. From this initial simulation, the internal isotropic stress in the polyimide film is estimated and used in the subsequent simulation runs as a starting point in a stress value sweep down to 0 MPa. Thereon, the deflection and capacitance of each cantilever may be calculated as a function of the stress.

One important point in the design of these bilayer systems is the establishment of a relationship between the water vapor concentration and polymer film swelling. To this end, a stress versus...
humidity plot has been drawn by relating stress values, derived from the FE modeling, to the experimental humidity values that yield the same capacitance change as the correlated stresses. In figure 6, the mechanical stress is plotted against humidity for various cantilever lengths (100 µm, 200 µm and 1000 µm). This plot confirms that the stress induced in the polymeric film depends linearly on relative humidity, which is in accordance with the findings of Sager et al [8].

In figures 7 (a) and (b), the measured capacitance is plotted as a function of humidity for 200 µm and 1000 µm long cantilevers. For comparison with the experimental data, the simulated capacitances versus stress curves are plotted. Good agreement is found between simulation and experiment.

![Image](image_url)

**Figure 7.** Comparison between simulated and experimental data for cantilevers with a length of (a) 200 µm and (b) 1000 µm.

4. Conclusions

The behavior of Si/polymer bilayer structures was approximated using finite element modeling. The FE model was applied to recently developed capacitive type humidity sensors where polyimide was used as a chemically sensitive layer. Good agreement with the experimental data was obtained for both initial deflection of the cantilevers and device capacitive change as a function of humidity. The induced film stress due to polyimide film swelling was found to depend linearly on humidity.

5. References

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