Performance analysis of in-plane piezoelectric unimorph microactuators based on silicon and polymer substrates

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Abstract. This work describes the performance in terms of displacement of two different in-plane piezoelectrically-actuated microactuators: a gripper and an extensional actuator. The materials and the corresponding thicknesses were varied in search of the best configuration for maximum displacement. Three different combinations of materials were considered: AlN/silicon, AlN/polyimide and PVDF/polyimide. A static finite element analysis allowed the calculation of the in-plane displacement. Reduction in the displacement per volt was observed when the thickness of the structure was increased. Despite the fact that polymeric materials are significantly less stiff than silicon, having potential advantages, our simulations reveal that it does not translate into the corresponding improvement in displacement per volt.

1. Introduction
For many years, the creation of devices capable of operating in a reduced scale has been one of the most pursued challenges in the technological world. Advances in technology and fabrication methods has allowed producing devices in the micrometre scale known as MEMS (microelectromechanical systems). MEMS, based on mechanical parts and electronics components, combine low power consumption and high performance characteristics. Remarkable applications of MEMS has been achieved in different fields such as medicine, biology, robotics or fluidics [1-4].

Microactuators are an essential component of the former group. These devices have the potential of producing forces and displacement in their mobile parts, allowing them to interact with different objects. Several applications of microactuators required in-plane movement such as gripping, stroke amplifying or micropositioning [5-7].

In order to produce this movement, actuators can be driven by electrostatic, thermal, electromagnetic or piezoelectric [8-11] forces. We focus on piezoelectric materials, due to the possibility of implementing an all-electrical scheme, that allows for actuation and self-sensing. Common piezoelectric microactuators are silicon-supported, what results in high forces and low displacements. However nowadays there is also interest in the possibility of achieving very high displacements or low forces for applications such as soft materials assessment. And here is where other materials or thicknesses might play a new role [12-14].

The objective of this work is to study how the in-plane displacement of two types of actuators, an extensional actuator and a gripper, varies depending on the materials under use, as well as on the thickness of these materials. Here we compare three different combinations of materials: a rigid combination based on silicon as support and AlN as piezoelectric material; a soft combination based on PVDF and polyimide substrate; and a hybrid one combining AlN and polyimide. A Finite Element
model (FEM) allowed us to study the effect of the thickness of the different materials in the search for the maximum displacement.

2. Actuators Design
The case of study of this paper is based on two types of piezoelectric unimorph (also termed heterogeneous bimorph) actuators: symmetrical and asymmetrical. Figure 1 shows the cross section of the proposed structures. A symmetrical unimorph structure (depicted in figure 1(a)) consists of a substrate support with a piezoelectric layer between electrodes at each side of the substrate. The symmetrical design allows for in-plane and out-of-plane movements [15]. By using the electrodes configuration and the polarization direction shown in figure 1(a), in-plane movement can be achieved.

Asymmetrical unimorph structure (figure 1(b)) consists of a piezoelectric layer between electrodes joined to a substrate. Typically this configuration produces bending moment in the structure and, consequently, out-of-plane displacement. In-plane displacement can be implemented with this scheme by the proper design of the electrode layout [17].

Two types of devices were considered: an extensional actuator with a symmetrical unimorph configuration, and a gripper with an asymmetrical unimorph structure. In order to maximize the displacement of the actuators, topology optimization was applied [16,17]. The optimization approach allows for the simultaneous design of both the shape of the structure and the electrode profile. The materials used for the optimization were silicon for the substrate and AlN for the piezoelectric layer with thicknesses of 100 μm and 1 μm, respectively. Figure 2 shows the shape and the electrode profile obtained after the optimization process for a 1000x1000 μm² extensional actuator and 5000x5000 μm² gripper. The different colours in the electrode profile represents different polarities in the voltage applied.

Figure 1. Schematic representation of unimorph structure: (a) symmetrical; (b) asymmetrical

Figure 2. Schematic representation of the structure and electrode profile resulting from the optimization process: each colour means opposite voltage polarity (a) extensional actuator; (b) gripper
In the case of the extensional actuator, in-plane displacement can be obtained by covering the structure with just one electrode. Nevertheless, the optimization provides an electrode profile that maximizes the displacement. In the gripper model, additional restriction was included in the optimization problem with the purpose of avoiding out-of-plane displacement in the tip. It is worth pointing out that these two device designs are the result of the optimization algorithm for the particular materials and dimensions mentioned above. Other materials or dimensions would require the corresponding optimization task and the resulting structure and electrode profiles would not necessarily be the same. Nevertheless, we use these particular designs as a reference to compare the effect of changing materials and dimensions on the microactuator performance.

3. FEM model description

A Finite Element Method (FEM) analysis has been conducted in order to study the tip displacement of the extensional model and the jaw behaviour in the gripper. Although the materials and the corresponding thicknesses were fixed for the optimization study, these parameters were modified during the FEM analysis. Three different sets of materials have been considered for the substrate and the piezoelectric layer of each model: AlN/silicon, AlN/polyimide and PVDF/polyimide. Table 1 shows the physical properties of the materials used in the simulations.

During the simulations, the structure was clamped in one of its sides (shown in figure 3). A Direct Current (DC) analysis was performed with 100V applied. As previously mentioned, each colour represents different polarities, being the blue areas 100V and the red ones -100V. Furthermore, the thickness of the electrodes was neglected in the FEM calculations. The displacement produced by the piezoelectric effect was measured along the X axis for the extensional actuator (figure 3(a)). In the case of the gripper, due to the symmetry in the displacement, only the motion of one of the arms was measured along the Y axis.

| Material  | Young Modulus (GPa) | Poisson ratio | Density (g/cm³) | $d_{31}$ (pC/N) |
|-----------|---------------------|---------------|----------------|-----------------|
| AlN       | 344                 | 0.24          | 3.2            | 2               |
| PVDF      | 2                   | 0.34          | 1.76           | 19              |
| Silicon   | 130                 | 0.28          | 2.33           | -               |
| Polyimide | 2.3                 | 0.34          | 1.42           | -               |

Table 1. Electromechanical characteristics of the materials
With the purpose of meshing the model, 3D element type has been employed. Hexahedral elements with squared faces and second order of interpolation were selected. A total number of 200,000 volume nodes were generated.

4. Simulation results
In the first analysis preformed, the thickness of the piezoelectric layer was fixed to 5 μm (in the case of the symmetrical model divided into two layers of 2.5 μm) and the thickness of the substrate was varied in the range from 0.04 μm to 800 μm. The displacements per volt obtained in absolute value for each model are presented in figures 4(a) and 4(b). By observing both graphics, it can be noticed that the greatest value of displacement per volt is obtained when the thickness of the substrate is minimum in all the cases proposed. If we pay attention to the combinations where AlN is present, the displacement tends towards the same value as the substrate thickness decreases, as expected due to the negligible role of the substrate; while for thicker substrates, the AlN/silicon combination results in the lower displacement due to the higher stiffness of silicon in comparison with polyimide. The soft model, formed by polyimide and PVDF, offers the largest displacement when the substrate is thin, due to the lower stiffness of PVDF; and its behaviour is similar to the rigid AlN/silicon combination when the thickness increases. The differences between both cases (rigid and soft) are greater in the gripper design than in the extensional model. The hybrid design, formed by AlN and polyimide, exhibits low variability in its motion in a wide range of thicknesses of the substrate. As it can be observed, the

![Figure 3. 3D model and inset of the simulated designs: (a) extensional actuator; (b) gripper](image_url)
Variations on the thickness of the piezoelectric layer were also studied while the substrate was fixed to 8 µm. Figure 5 shows the behaviour of the displacement per volt in absolute value with varying thickness of the piezoelectric layer. As it can be observed, by increasing the thickness of the piezoelectric layer, the displacement of the tip decreases. In the case of the extensional design, the hybrid model exhibits the highest sensitivity to this parameter. For the gripper design it can be observed a similar behaviour.

![Figure 5. Displacement per volt in the tip of the actuator as a function of the piezoelectric layer thickness in a 8 µm substrate layer. (a) extensional actuator; (b) gripper](image)

5. Conclusion
A comparative study was carried out with different type of structures (symmetrical and asymmetrical), designs (extensional and gripper) and materials (AlN, PVDF, silicon and polyimide). The design of each model was obtained in a topological optimization process, with the purpose of maximizing the in-plane displacement. A static analysis was performed applying DC voltage in the electrodes and the resulting displacement produced in the tip was calculated for each model. Taking a topologically optimized layout as a reference, the thicknesses of the different layers and the materials were modified and its behaviour studied. A reduction in the displacement per volt was observed when the thickness of the structures was increased, independently of the layer varied. Even though polymeric materials exhibit significantly lower stiffness than silicon, an outstanding performance in terms of displacement per volt was not observed when they were used. Nevertheless, some materials combination suggest promising applications such as AlN and polyimide. This combination offers, for a wide range of substrate thickness, values of displacement per volt closer to the case where the thickness is negligible.

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