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## Dielectric Elastomer Micro Actuator Made In Micromachining Technology: Finite Element Modelling and Deformation Measurement

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### Abstract

In this contribution, we focus on polymer actuators based on dielectric elastomers, and intend to establish innovative and alternative integration miniaturization processes inspired from MEMS technology. We propose to use the polydimethylsiloxane (PDMS) due to its high elasticity and adjustable permittivity by addition of ceramic nanoparticles. A method for structuring PDMS layers is developed. It allows overcoming the technological challenges encountered during the integration of such materials in a micro-actuator. The fabrication of the functional actuator also involves a thin gold upper electrode, which is obtained by a lift-off process. We demonstrate the successful integration of micro-actuators, which generate at most 2  $\mu\text{m}$  displacements. In parallel the response of our actuator is analyzed quantitatively by modelling the elastomer response with hyper elastic models using FEM tool. We show excellent agreement between the model and experimental deformations.

© 2011 Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](http://creativecommons.org/licenses/by-nc-nd/3.0/).*Keywords:* elastomer; PDMS; Actuator ; EAP ; hyperelastic model ; FEM

### 1. Introduction

In the late 90's, Bar-Cohen [1] presented a review of polymer materials which can be considered as electro-active materials. The dielectric elastomers are one of the proposed categories. In 1998, Pelrine [2] emphasized on the possibilities to use many commercial polymers for realize actuators with dielectric elastomers. Since then, many research groups worldwide are working on this type of actuators. Several teams have specialized in integration [3], characterization [4-5] and modeling [6-7] of such materials. Thus, these polymer dielectrics are generally put forward for the fabrication of biomimetic actuators for

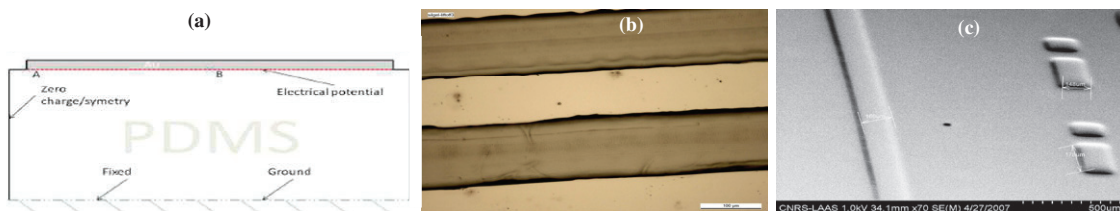
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robotics and mechatronics [8]. Nowadays, the dielectric devices are of large dimension due to the manufacturing techniques. The possibility to miniaturize has not been taken into account. In this paper, we will present a manufacturing technique allowing to reduce typical sizes and to take advantage of microsystems technologies. After, actuation and modeling results are exposed.

## 2. Materials and Fabrication

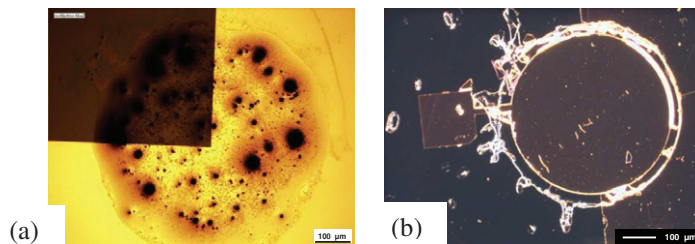
These actuators are in general constituted by a polymer film sandwiched between two compliant electrodes. When a voltage is applied, an attractive force between the electrodes generates a mechanical displacement that depends on the Young modulus of the elastomer and its permittivity. The actuation deformation ( $\gamma$ ) is proportional to elastomer permittivity ( $\epsilon$ ) in virtual electrode model and inversely propositional to elastomer Young modulus ( $Y$ ):  $\gamma = \epsilon \epsilon_0 E^2 / Y$ , where  $\epsilon_0$  is the air permittivity and  $E$  is the applied electrical field. In our study, we have realized a miniaturized actuator based on a stack of polydimethylsiloxane (PDMS) embedded within two gold electrodes where the bottom electrode is fixed, top electrode is free and can be attracted under actuation (figure 1a).

To achieve this, the elastomer is patterned on the wafer and is made photosensitive whereas the gold electrode is evaporated by a PVD process with conventional lift-off method. For the elastomer choice, we pitch on commercial PDMS formulations already used on micro-fluidic and which could be used in an electrostatic actuator. This material is sold in solution making spin coating easier. That is why we have directed our work towards a method of integration compatible with conventional micromachining technology. We investigate a category of bi-component silicones cross-linkable at room temperature because their cure is easier to adapt in a process of integration compared to hot cross-linkable rubber, which is more rigid. We selected the PDMS Silgel 612 from Wacker which has a very low Young's modulus (5kPa) in comparison with other PDMS materials such as Sylgard series because the electrostatic pressure is proportional to the inverse of Young's modulus. To achieve this purpose, we chose to use a photo active component leading to a material that acts as a positive resist. Benzophenone has been chosen to play this role and best results are obtained for concentrations of 2 % wt of benzophenone in PDMS. The benzophenone acts as an inhibitor of crosslinking after activation by UV. In non-irradiated regions, cross-linking is accelerated. In the exposed parts, this crosslinking is delayed by benzophenone activated during exposure. The best selectivity between the exposed parts and non-irradiated require post-bake step. The optimum was found for 150 ° C and 30s. Below this time, the crosslinking of the non-irradiated is not sufficient to get selectivity during development. We use tetrahydrofurane (THF) as a developer because its solubility parameter is very close to that of PDMS [9]. Very soft PDMS like Silgel 612, led us to implement a second method of manufacturing based on lift-off [10], in order to obtain a flat surface and straight edges (figure 1b and 1c). It is worth mentioning that a fonctionalization step is required to adapt PDMS patterning on gold surface because the PDMS is rather hydrophobic and gold is rather hydrophilic. Therefore, we used molecules that have alkanethiols functionalized sulfur (S) groups compatible with many metals (Au, Cr, Al, etc.) and a hydrophobic alkane groupment compatible with PDMS. We chose to use 1-octadecanethiol from Sigma-Aldrich [11].



**Fig 1:** (a) schematic presentation of dielectric elastomer micro actuator, (b) Optical microscopy photo (left) and (c)MEB image of pattern Silgel 612 obtained by the alternative Lithography process.

A way to improve the performance of this type of actuator is to increase the permittivity of PDMS because the actuation force is proportional to the elastomer permittivity. We loaded PDMS with particles having a high permittivity. We have added those nanoparticles at the beginning of the process that is to say in the formulation with the PAC. Dispersion of nanoparticles is obtained by ultrasonic process at 80 kHz during 3 minutes. For this, we adopted  $\text{TiO}_3\text{Ba}$  from Sigma Aldrich (size 70-130 nm). The resulted roughness of the deposited layer depends on the size of the clusters formed by  $\text{TiO}_3\text{Ba}$ . In addition, this roughness depends on the thickness of the deposited layer. It was noted that the roughness becomes negligible (about 50nm) for a thickness less than 40  $\mu\text{m}$ . That is why we have chosen a size of nanoparticles powder as small as possible. The relative permittivity measurements show that adding nanoparticles of barium titanate allows a significant increase in the dielectric constant of Silgel 612 from 2.7 to 3.3 for 10 wt%  $\text{TiO}_3\text{Ba}$ . However, we are limited to a thickness of at most 40 $\mu\text{m}$  in order to maintain an absence of surface roughness. Also, the larger is the weight fraction of nanoparticles, better is the permittivity of the mixture, but in the same way the resolution decreases. It should be noted that the resolution of charged material (10% in weight) is roughly two times lower compared to resolution without nanoparticles.

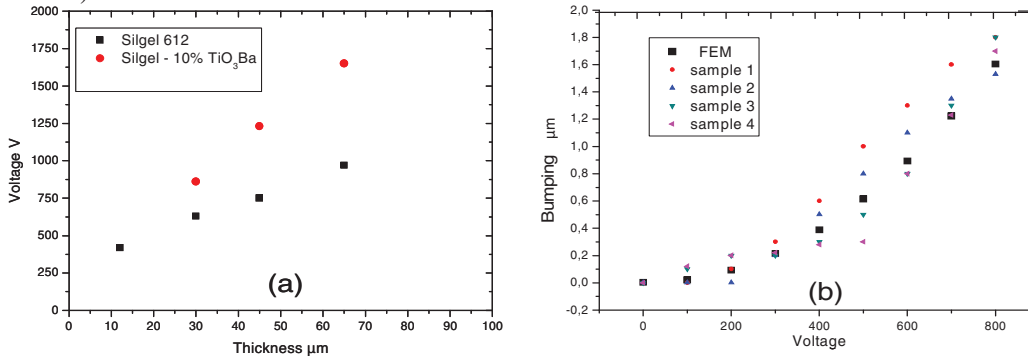


**Fig 2:** Optical microscopy photo of pattern Silgel 612 charged with 10% wt of  $\text{TiO}_3\text{Ba}$  obtained by the alternative process inspired from lift-off process (a) on bottom electrode and silicon (b) with top electrode.

### 3. FE modeling and deformation measurement

To measure the deformations induced by applied voltages, we used an optical interferometer from Fogale Nanotech society. All measurements were made by white light interferometry. We observe that micro-actuators can exhibit non-uniform deformation with compression at the edge and bumping in the center of the pattern for the design cited above. On samples with Silgel 612 (45  $\mu\text{m}$  in thickness and 500  $\mu\text{m}$  in width) with gold top electrodes (100 nm), we expected to observe deformations of the order of the micron. However, we noted a slight shift at the free edge of the upper electrode (the deformations are of the order of 200 nm) before reaching the breakdown voltage of the PDMS. We noticed electrical discharge (corona type) between the two electrodes before this phenomenon. We could measure the breakdown voltages for each thickness of PDMS Silgel 612. Figure 3a illustrate the breakdown voltages of Silgel 612 with and without nanoparticles  $\text{TiO}_3\text{Ba}$  as function as elastomer layer thickness. These results are four times lower than the measurements on PDMS Sylgard 186 and CF19 Nusil by Rosset et al [12]. These authors demonstrate that this property depends on the electrode nature and they measure breakdown electric fields between 100 and 140  $\text{V}/\mu\text{m}$ . Our measurements provide average values of 16 $\text{V}/\mu\text{m}$  for Sigel 612 and 28 $\text{V}/\mu\text{m}$  for Silgel 612 with 10%  $\text{TiO}_3\text{Ba}$ . The use of hyperelastic models coupled with the electrostatic mode, through the Comsol Multiphysics tool for FEM, enabled us to compare this results. In our study, we use the Mooney-Rivlin model since it is the most used in the dielectric elastomer actuator simulation. The limits conditions are described in figure 1a. We choose to pursue a 2D modeling [13] to reduce the computation time and make the approximation of plane strain considering a cross section of an actuator infinite in the third direction. The figure 3b shows that the

actuation deformation corresponds to a hyperelastic behavior. The fact that the dielectric breakdown is greater with an elastomer loaded with  $\text{TiO}_3\text{Ba}$ , makes the change of the composition extremely beneficial knowing that we will improve further the electrostatic pressure and therefore lower the actuation voltage. This phenomenon is analogous to the case of acrylates [2] where a pre-stretching of the film increases the dielectric strength. In our case, if we want to increase the elastomer dielectric strength, we must use higher proportions of  $\text{TiO}_3\text{Ba}$ . However, the load may also limit the production process (impact on the resolution).



**Fig 3:** (a) Comparison of the breakdown voltages between the Silgel 612 and silgel 612/ $\text{TiO}_3\text{Ba}$  as a function as the thickness of the layers, (b) Comparison between FE modelling and measuring the thickness of a pattern of 500 microns for a layer of Silgel/ $\text{TiO}_3\text{Ba}$ , depending on the applied voltage of 45 $\mu\text{m}$  thick.

#### 4. Conclusion

We have realized a miniaturized actuator based on a stack of polydimethylsiloxane (silgel612) embedded within two gold electrodes where the bottom electrode is fixed and the top electrode is free and can be attracted under actuation. To increase the pressure, we have modified the dielectric properties of the material. For this, we formulate PDMS with high permittivity ceramic nanoparticles. The relative permittivity measurements have pointed out that adding nanoparticles increases the dielectric constant and the breakdown voltage. This study demonstrates that the actuation of an elastomer charges with  $\text{TiO}_3\text{Ba}$  nanoparticles follows a hyperelastic behavior. This result is particularly helpful for the design of a micro-actuator in a given application.

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