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Improved manufacturing process for printed cantilevers by using water removable sacrificial substrate

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ABSTRACT

Suspended structures are an important element in the vast majority of electromechanical systems. The definition of this kind of structures is a not totally resolved problem in printing electronics where the definition of a smooth sacrificial layer makes difficult their fabrication. Based on a previous work using a sacrificial substrate, we present in this paper a significant improvement of this technique in terms of reproducibility and yield rate. The sacrificial substrate is a commercial polyvinyl alcohol film which can be removed by water. The structural material is silver paste which has shown better performance during the removal of the sacrificial substrate than the previous approach based on an acetone bath. Furthermore, this sacrificial material is biodegradable as well as its solvent. In this paper, we show the fabrication process for printed cantilevers, including a characterization of their peak to peak displacements as a function of the applied acceleration and frequency. Moreover, the variation of the capacitance for different acceleration values is presented.

1. Introduction

Suspended mechanical structures are useful in many different applications such as accelerometers, pressure sensors, actuators or fluidic devices [1]. Traditionally, these structures have been manufactured with micro-electromechanical system (MEMS) fabrication techniques and integrated with CMOS technology [2]. With this regard, the deposition of a sacrificial layer to support and define the suspended part while manufacturing is essential. This layer is removed at the end of the fabrication process depending on the particular process that is being used. Although many different strategies and materials have been used to fabricate these suspended structures based on silicon MEMS technologies, there are other processing technology platforms such as printed electronics where this development is not so advanced yet.

The advantages of printed electronics such as low-cost equipment, flexible substrates, low-cost materials, degradability and biocompatibility, open a wide range of new applications for example, radio frequency identification (RFID) tags, smart clothing or flexible displays. This technology is based on traditional printing techniques, such as gravure, screen printing, flexography and inkjet printing [3]. Many advances have been achieved in devices such as organic light-emitting diodes (OLED), thin film transistors (TFT), solar cells and printed antennas [4,5] but there are still some aspects that should be improved in terms of performance and reliability.

Great efforts and very valuable achievements have been done to develop printed sensors, mainly chemical sensors, and bioelectronics, but limited developments have been achieved in mechanical suspended structures. One of these not-resolved aspects is suspended structures by using only printing techniques. The main problems to face with respect to surface micromachining process are the smoothness of the sacrificial layer, its removal process [6], the stability of the pillar on a plastic substrate and the roughness of the plastic film. The sacrificial layer has to be smooth to properly define another layer on top of it. In addition to this, the removal method should not affect the rest of the layers. The most common method to remove the sacrificial layer is the chemical bath. It is not easy to find suitable materials to act as sacrificial layer, whose solvents do not affect the structural materials. The mechanical properties of the structural material are fundamental to the stability of the suspended structure but, with respect to the flexible substrate, it results more complicated to maintain the suspended part when the substrate is not rigid.

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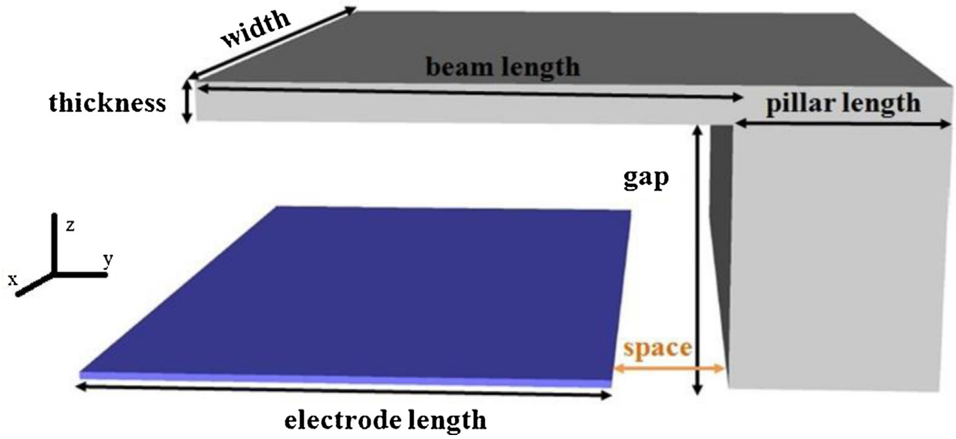

Fig. 1. Schematics of the cantilever.

Regarding the sacrificial layer, different strategies have been followed to reach these requirements. Lam et al. [7] used a poly(methyl methacrylate) (PMMA) sacrificial layer to develop a cantilever by screen printing with a releasing method based on chloroform baths followed by drying with a N_2 gun. Park et al. [8,9] also chose PMMA as sacrificial layer. PMMA was also chosen as sacrificial material by Chung et al. [10] to develop 4-terminal inverters. They removed the sacrificial layer by dipping into boiling acetone and isopropyl alcohol. This latter material was removed in an acetone bath to release a switch made by inkjet printing. Another used sacrificial layer has been a strontium carbonate ($SrCO_3$) in an epoxy-type ink which is dissolved by immersing the structure in a weak acidic solution [11,12]. Nathalie Serra et al. [6,13] employed a solution based on trimethylolethane removed by thermal treatment to develop bridges and cantilevers by screen printing. Another sacrificial layer used to manufacture bridges by inkjet printing was a commercial photoresist Microposit® 1813® from Shipley [14]. In this case, the sacrificial was removed by dissolving it in acetone. Shankar et al. [15] selected PMMA as sacrificial layer to develop ohmic contact RF MEMS switches and this layer was dissolved by soaking the structure in chloroform.

In regard to the used substrates, Fuller et al. [16] developed silver cantilevers on glass by inkjet printing. A silicon substrate was used by Park et al. [8] to fabricate printed switches and to develop 4-terminal inverters [10]. Wei et al. [17–21] fabricated piezoelectric cantilevers on cotton by screen printing. Alumina substrate has been chosen to manufacture suspended structures for several authors [6,12,13,22–24]. A few examples can also be found using plastic surfaces: a microelectromechanical switch developed on polyimide substrate by lamination techniques [25,26], switches on Kapton polyimide [15], electrostatic microactuators made of a flexible sheet [27], or printed bridges on polyethylene terephthalate (PET) [14] or a cantilever also developed on PET by screen printing [28]. In this previous work, the design, fabrication and characterization of a printed cantilever were reported.

Here, we present some advances in the fabrication of a printed cantilever on a plastic substrate. As described in our previous work [28], our fabrication process differs from others on the use of a commercial film, PMMA, as sacrificial material. The main difference remains in the role of this layer: it is also used as a substrate for printing the beams and the pillars, and then this substrate is flipped and bonded to the printed electrodes substrate. These electrodes had been previously printed on another substrate. After a bonding process, the sacrificial substrate is removed. The structure presented here are essentially made using the same process flow, but while in our previous work the sacrificial substrate had to be chemically etched, we have used now a different material so that it can be eliminated with a different solvent without virtually inferring with the structural material. Hence, while we stated that our previous process was similar to the wafer bonding procedure developed to obtain Silicon-On-Insulator wafers in microelectronic technology, this new procedure is similar to the Unibond™ method that does not require to etch the whole wafer [29]. An important advantage of this new procedure is that there is no degradation of any layer during the removal of the sacrificial substrate because it is a layer of transference. In addition to this, the substrate is a plastic substrate, which provides more flexibility to the final device but less stability during the manufacturing process of the suspended structures.

2. Materials and methods

2.1. Design

To design this structure, we have implemented the same approach we developed in our previous work [28] to directly compare results. Given the complicated geometry of the printed cantilever, we skipped the development of an analytical model and we directly used a multiphysics numerical simulator, COMSOL (Comsol Inc., Stockholm, Sweden), based on solving partial differential equations with the finite element method. This software has previously been used to calculate displacements and resonance

Table 1
Dimensions of the designed suspended structure.

Parameter	Value	Description
Length (mm)	5.0	Length of the beam
Width (mm)	2.5	Width of the beam
Gap (μm)	120	Distance between the back electrode and the beam (*z*-axis)
Space (mm)	1.0	Distance between the back electrode and the beam (*y*-axis)
Thickness (μm)	15	Thickness of the beam

Table 2
Comparison between numerical and experimental physical dimensions of the cantilever beams with PMMA layer and PVA layer.

Parameter	Model	Experimental PVA procedure	Experimental PMMA procedure [28]
Length (mm)	5.0	4.97 ± 0.05	4.98 ± 0.05
Width (mm)	2.5	2.56 ± 0.06	2.59 ± 0.05
Gap (μm)	120	125.7 ± 1.5	132 ± 2
Thickness (μm)	15	16.8 ± 0.1	17.3 ± 0.1
Capacitance (pF)	3.85	3.62 ± 0.01	3.51 ± 0.01