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Capillary origami of micro-machined micro-objects: Bi-layer conductive hinges

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ABSTRACT

Recently, we demonstrated controllable 3D self-folding by means of capillary forces of silicon-nitride micro-objects made of rigid plates connected to each other by flexible hinges (Legrain et al., 2014). In this paper, we introduce platinum electrodes running from the substrate to the plates over these bendable hinges. The fabrication yield is as high as $(77 \pm 2)\%$ for hinges with a length less than 75 μm. The yield reduces to $(18 \pm 2)\%$ when the length increases above 100 μm. Most of the failures in conductivity are due to degradation of the platinum/chromium layer stack during the final plasma cleaning step. The bi-layer hinges survive the capillary folding process, even for extremely small bending radii of 5 μm, nor does the bending have any impact on the conductivity. Stress in the different layers deforms the hinges, which does not affect the conductivity. Once assembled, the conductive hinges can withstand a current density of $(1.6 \pm 0.4) \times 10^6$ A/cm^2. This introduction of conductive electrodes to elastocapillary self-folded silicon-based micro-objects extends the range of their possible applications by allowing an electronic functionality of the folded parts.

1. Introduction

Pushed by the semiconductor industry, lithography-based fabrication techniques now include new methods other than UV illumination: mask-less projection of laser light, electrons and ion beams, etc. Extremely precise, these methods are nevertheless inherently two-dimensional. They essentially consist on patterning one single layer after the other. Precise three-dimensional (3D) shapes can be obtained using anisotropic etching of silicon, but they are constrained in depth or height because of a limited substrate thickness. Consequently, high aspect-ratio structures are difficult to fabricate using techniques based on lithography and etching [2,3].

One solution is to fold structures out of the plane of fabrication, preferably by self-folding. Self-folding broadly refers to the self-assembly of interconnected parts that fold themselves into predefined shapes without the need of active human control. The assembly is either triggered by external stimuli (e.g., pH or temperature variation), enabled by external forces such as magnetic forces, or by internal forces such as pre-stressed layers [3–5]. Three-dimensional assembly of micro-/nano-objects is possible using self-folding, where inherently two-dimensional micro-fabrication techniques have been shown to be inadequate [2].

Capillary origami designates the self-folding of flexible elastic material using surface tension as the enabling force [6,7]. Capillary origami is a particularly interesting tool for micro-fabrication, since at small scales, surface forces dominate over bulk forces such as gravity [8,9]. This technique was first employed to assemble silicon-based micro-objects by Syms et al., who used melting solder to assemble hingeless silicon objects with integrated metal pads in flaps [10,11]. The scope of such solder assembly was then extended by Gracias et al., who demonstrated the folding of complex structures (cubes, pyramids…) of micrometer and nanometer sizes fabricated using standard lithography and deposition techniques [12–15]. Applications of such structures range from three-dimensional micro-opto-electro-mechanical systems (MOEMS) [16–18] to RF nano-antennae [19].

We have used capillary origami to fold silicon nitride micro-objects. Unlike in solder assembly, the structures are necessarily hinged and their folding relies on the deformation of thin flexible silicon nitride plates, therefore the method can also be called elastocapillary folding. The folding is driven by the surface tension of water, which is simply manually deposited [20,21] or brought to the origami pattern through a tube at its center [1]. The final shape of the object is predefined by the patterning of rigid silicon nitride plates that form the body of the 3D object, linked to each other by hinges. Objects remain assembled due to strong stiction between the flaps [20,1] or by designing complex stop-programmable hinges [21].

The applications of this self-folding technique are limited to situations where a passive mechanical structure is required that extends far above the wafer surface. To extend the range of applications, it would be extremely useful if electrical connection can be made to the moving parts of the folding structure. Electrical conductance over hinges has been demonstrated in experiments where folding is

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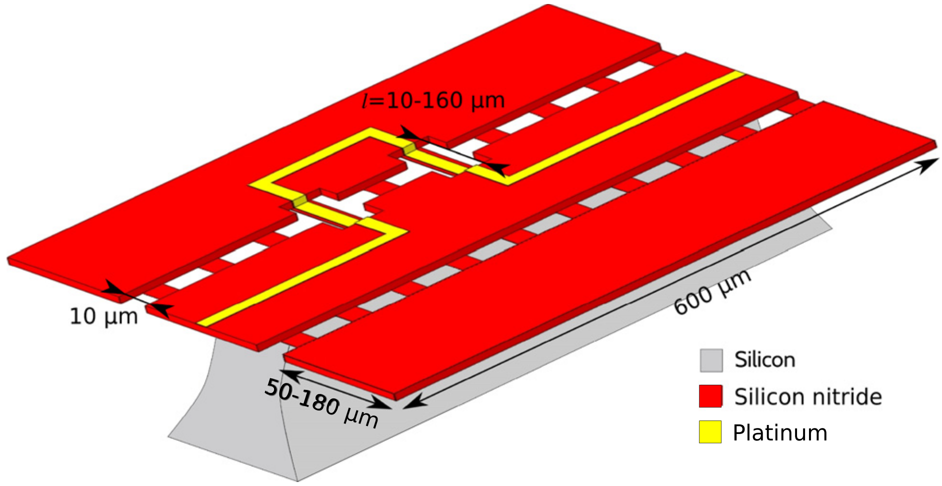

Fig. 1. Concept image of a typical test structure. Two free hanging silicon nitride flaps are connected to the central part by means of thin flexible silicon nitride hinges. The central part is fixed, resting on a silicon pillar. In this example, two decoupled bi-layer hinges run along the center of the structure. The length *l* of the metalized junctures can be tuned, while the plain SiRN hinges are always 10 µm long. The metal parts run to contact pads on the outside of the structures.

achieved by magnetic lifting [22,23] or stress gradients [24,25]. In this research we have combined electrical connectivity with folding by capillary forces. Fig. 1 shows the type of structures used to prove the feasibility of conductive hinges. Structures based on our previous publications [20,1] are extended with platinum wires that run from the substrate towards the flap via bendable hinges. After elastocapillary folding, a three-dimensional triangular prism structure ('Toblerone' [26]) is realized, which has electrical wiring on its movable parts.

The requirements for the electrode material are a high electrical and thermal conductivity to reduce power loss and unwanted heating, in combination with a low Young's modulus to keep the hinges as flexible as possible. Gold would therefore be an excellent candidate. However, as possible application of elastocapillary folding we consider out-of-plane flow sensors. Since these sensors need to operate at high temperature, additional requirements such as high melting point ($T_m = 1768$ °C) [27], high temperature coefficient of resistance (TCR, 3.1/°C to 4.3×10^{-3}/°C) over a wide temperature range (0 °C to 800 °C) [28] and high oxidation resistance are crucial. In this work, we therefore selected platinum as the material of choice.

In the following we will discuss shortly the stress induced by folding and the effect on electrical resistance and explain the fabrication process. Subsequently we demonstrate that conductivity can be preserved

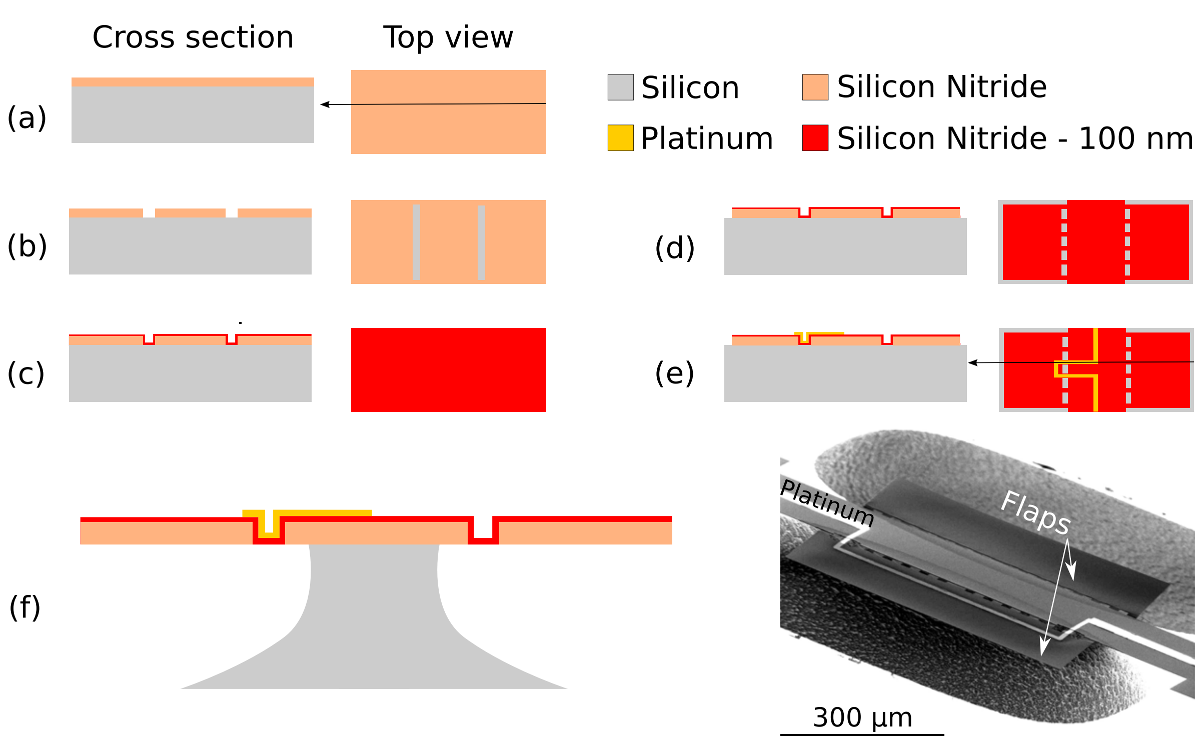

Fig. 2. Fabrication steps for silicon nitride (SiRN) structures with integrated conductive hinges capable of being folded out of the plane by capillary forces. (a): Deposition of SiRN by LPCVD. (b): First lithographic step; definition of the hinges. SiRN is either dry or wet etched. (c): Second deposition of SiRN. (d): Overall definition of the structures by a lithography step and subsequent dry etching. (e): Sputtering of metal followed by a standard lift-off procedure. (f): Release of the flexible objects by semi-isotropic etching of silicon. The SEM picture on the right hand side shows an example of a final structure.