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A novel fabrication process for capacitive cantilever structures for smart fabric applications

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Abstract: **This paper reports, for the first time, capacitive free-standing cantilever beams fabricated by screen printing sacrificial and structural materials onto a fabric/textile. Unlike traditional weaving process, the device will be screen printed layer by layer with desired pattern onto the fabric substrate. Free standing structures will be fabricated directly onto fabrics rather than other methods such as bonding or embedding. In addition, a low temperature removable sacrificial material capable for the removal conditions on fabrics will also be reported.**

I. Introduction

Smart fabrics offer functionality by integrating electronics, sensors and actuators within the garment, typically by weaving or knitting active yarns [1]. They have been widely researched for healthcare, consumer, fashion and military applications [2]. Electronic functions, such as conduction, is typically achieved by either weaving or knitting custom yarns with the appropriate functionality in the fabric structure or by embroidering them on top of the fabric [3-5]. However, screen-printing is an attractive alternative solution for smart fabric fabrication because printing allows significantly more freedom in the device orientation and placement on the fabric when compared to the custom yarn based approach. This is because any printed structures do not have to follow the yarn structure of the fabric. In addition, it is already widely used in the fabrics industry for colour patterning. Finally, this approach is suited to large scale production.

The device described in this paper is a capacitive cantilever, a structure which finds widespread application in Micro-Electro-Mechanical Systems (MEMS) based sensors and actuators. MEMS Cantilevers have been used as the basis for a wide variety of sensors and actuators such as accelerometers, flow sensors or thermopiles. We report here early steps towards the migration of MEMS sacrificial fabrication techniques on to fabrics. *C.R. Merritt. et. al.* have already demonstrated textile based capacitive sensors fabricated on a chest belt using bonded aluminium and copper foils on fabric [6]. This sensor was partially screen-printed but the overall assembly is incompatible with batch fabrication. We report here a batch fabrication process for capacitive devices based on screen printing with the specific example of a cantilever. Screen printing uses materials in a paste form which are printed through a pre-patterned screen. The pattern on the screen defines where the paste is deposited on the fabric. A sacrificial paste must provide a solid support layer after printing and curing which is subsequently removable. This removal should be achieved by a subsequent processing step such as an additional thermal or chemical treatment. Additionally, the removal process should not damage either the layers we wish to keep (e.g. structural or conductor layers) or the underlying fabric. Options for the removal process are further limited since fabrics cannot withstand either high temperature (>150-200 °C depending on the fabric) or aggressive chemicals such as strong acids or solvents.

The sacrificial material developed in this work is based on Trimethylolethane (TME) which is a plastic crystalline material. TME has an exponential increase in its vapour pressure once the temperature exceeds the transition temperature (~83 °C) [7]. Due to its high vapour pressure, this material will maintain the solid phase with minimal sublimation until the temperature approaches its melting point (187 °C). This is a great advantage since this material provides a stable solid state during the printing of subsequent layers. The plastic crystal transition temperature of TME is approximately 83 °C depending on the purity. As the temperature is increased, the vapour pressure of TME is exponentially increased, as shown in Fig 1. Fig 1 also includes the vapour pressure as a function of temperature for Cyclohexanol (CH) and propylene glycol (PG) which are used

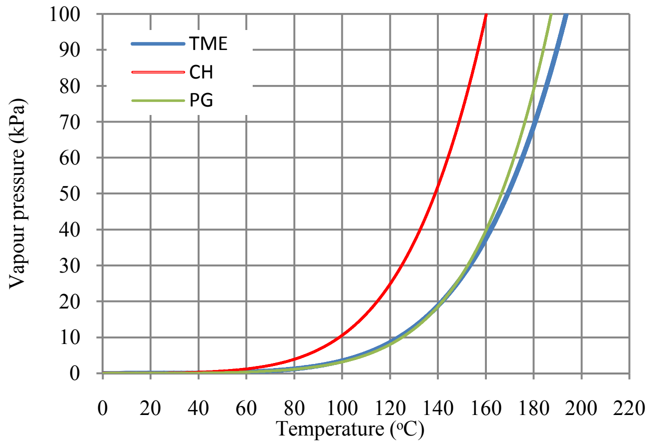

Fig 1 Vapour pressures against temperature of the primary compounds [7]

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in the formulation of the sacrificial paste. It is important that these materials respond to temperature similar to TME so that all three materials sublimate at a similar rate during the removal process.

We have chosen 65% Polyester 35% Cotton fabric for the substrate material since this is the most widely used fabric for clothing (supplied by Klopman International) [8]. This fabric can withstand a maximum temperature of 160 °C. This temperature is therefore the maximum which can be used for the removal process. However, the melting temperature of TME is around 187 °C so the required removal time is increased from a few seconds at 187 ^{o}C to 30 minutes at 160 ^{o}C to provide complete removal of the TME.

II. Experimental procedure

TME is soluble in many solvents, allowing the formulation of a screen printable paste. The principle of the formulation is based on a 'like-dissolves-like' rule which means the solute and solvent should have the same polarisation. The solid TME powder can be dissolved into another liquid plastic crystal at 100 °C to achieve a homogeneous solution. The liquid state plastic crystal used in this work is Cyclohexanol (CH), which has a plastic crystal transition temperature of -28 °C [9]. However, CH has a melting temperature of 25 °C; propylene glycol (PG), which is a viscous alcohol, is used to lower the melting point below 25 °C to provide a liquid solvent [10].

Table 1 Dimensions of the four cantilevers.

Sample number	1	2	3	4
Beam (mm)	9×10	12×10	15×10	18×10
Electrode (mm)	8×8	11×8	14×8	17×8

Electra Polymer EFV4/4965 is used for the structural material as it provides good printability and mechanical properties. Johnson Matthey S-20 silver paste is used for the

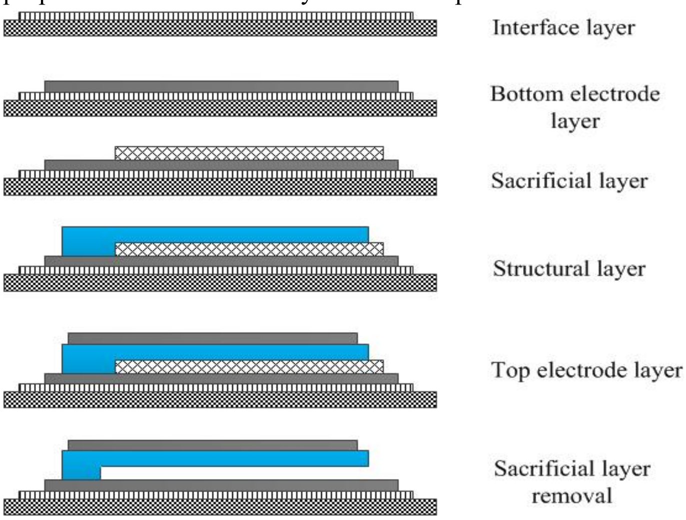

Fig 2 Printing sequence of the capacitive cantilever

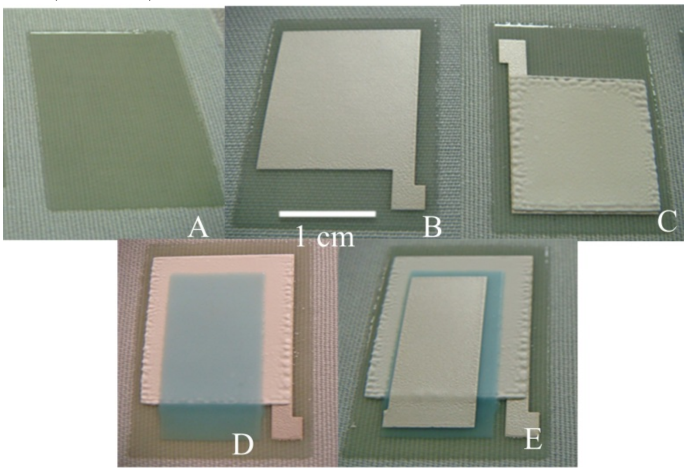

Fig 3 Printing stages for the free standing cantilever capacitor structure. A- interface layer, B – bottom electrode, C-sacrificial layer, D- structural layer, E – top electrode

two capacitor electrodes as it provides good conductivity, adhesion and flexibility. A capacitance-based cantilever is screen printed on top of the fabric by using the materials described above. A separate screen is manufactured for each layer and will produce four cantilever structures per substrate. In order to examine the performance of the cantilever at different frequencies, four cantilever beams with lengths of 9, 12, 15 and 18mm were printed. The full dimensions of the cantilever and electrodes are shown in Table 1. These dimensions were chosen to produce a mesoscale device to allow straight forward visual examination and handling of the device during process research. The ultimate resolution of this technology should produce devices of dimensions ~200µm which is expected to be sufficient for the majority of fabric based applications. The printing and sacrificial process sequence is shown in Fig 2 and Fig 3.

Due to the surface roughness of the fabric, an electrically insulating interface paste, Fabink-UV-IF1, supplied by Smart Fabric Inks Ltd, is used to achieve a smoother surface for subsequent printing. This paste was first printed on the fabric followed by S-20 to form the bottom electrode. The sacrificial layer was then printed and dried at 80 °C for 10 minutes. Then the structural layer, EFV4/4965, was printed on top of the sacrificial layer and UV cured. Finally, the top electrode was printed and dried at 120 °C for 3 minutes. For the removal

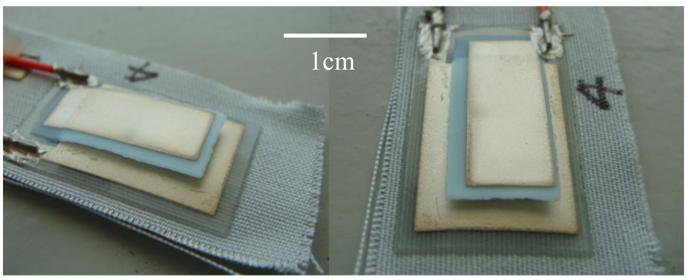

Fig 4 Cantilever capacitor sample after the removal process

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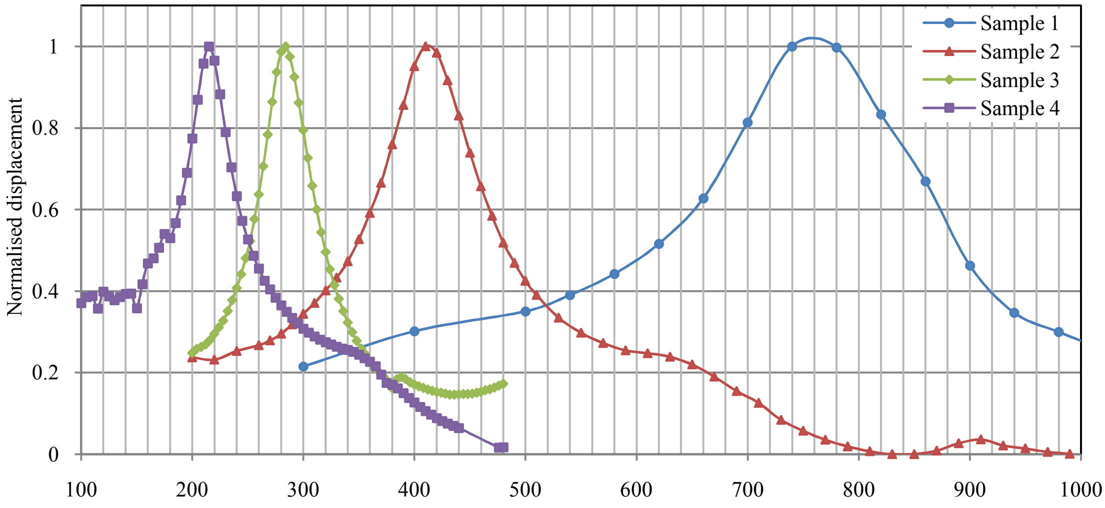

Fig 5 Normalised displacement versus frequency

process, the samples were placed in an oven at 160 °C for 30 minutes.

III. Results

The samples were examined by microscope, confirming that the sacrificial layer was fully removed leaving no residue. The structures were therefore completely released from the substrate to form free-standing cantilevers. Fig 4 shows a typical cantilever after removal of the sacrificial material from the substrate. However, a small amount of curling occurs during the 160 °C removal process which softens the printed materials resulting in an uneven distribution of stress. This curling has an effect on all of the printed layers which reduces the gap between the beam and the substrate. However, there is no delamination or cracks in the final structure. The removal temperature does not damage the fabric and is within its operating temperature range.

To check the functionality of the device capacitors, the four cantilevers were measured using a Wayne Kerr LCR meter and the results are shown in Table 2.

Table 2 Static capacitances for each cantilever capacitor structure

Sample number	1	2	3	4
Measured value (pF)	3.94	6.02	6.29	7.59

To evaluate the dynamic performance of the cantilever structure a purpose built shaker rig was used to measure the cantilever deflection as a function of frequency. Each device was individually tested by mounting it on the shaker whilst a laser beam was focused on the tip of the cantilever to measure the deflection. Fig 5 shows the normalised displacements of the cantilever versus the frequency with a vibration acceleration of $2g_{rms}$.

For a thin cantilever beam, the natural vibration frequency can be written as [11]:

$$f_i = \frac{\lambda_i^2}{2\pi}\left(\frac{t}{2L^2}\right)\sqrt{\frac{E}{\rho}} \qquad (1)$$

where λ_i is a coefficient based on the clamping conditions, t and L are the thickness and length of the beam respectively, E and ρ are the Young`s modulus and density of the beam material. Fig 6 shows good argeement with equation (1) in that the resonant frequency is inversely proportional to the length squared of the cantilever. This also implies that E, t, ρ and λ_i are constant between different devices.

IV. Conclusions

This paper reports for the first time a screen printed capacitive free standing structure on a fabric substrate using low temperature sacrificial technology. The results have shown that the sacrificial material is completely removed from the substrate to form free standing cantilever beams. A

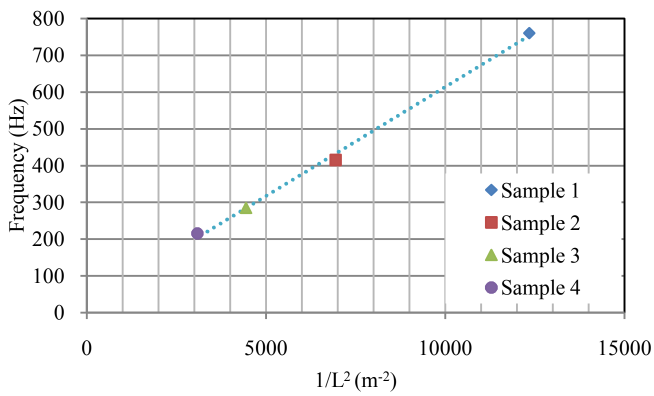

Fig 6 Frequency versus $1/L^2$

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Trimethylolethane (TME) based sacrificial material was successfully formulated to achieve a printable sacrificial layer which could be cured at 80 °C and allowed subsequent materials to be printed on top. This TME layer was subsequently removed at 160 °C for 30 minutes to release the cantilever. Confirmation that the beam was free standing was achieved by inspected with a microscope and the use of a shaker to determine the movement of the beam under acceleration.

Future work will achieve further characterisation of the beam and determine the dynamic change in capacitance due to vibrations. In addition, having confirmed the process, the sacrificial fabrication technology can be applied to realise other sensors such as accelerometers and pressure sensors.

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